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THE UNIVERSITY OF ALBERTA

THE EFFECT OF PRESTRAINING ON THE TRANSITION TEMPERATURE OF MILD STEEL

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE IN CIVIL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

by

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ABSTRACT

The effect of prestraining on the transition from tough to brittle behavior of a mild 0.15% carbon steel is investigated using standard V-notch Charpy test specimens. A review of technical literature on the subject is made and summarized.

Five strain conditions were chosen, namely, no prestrain, strain just below the yield point, 2.5%, 4.9% and 9.7% prestrain. Straining was done in tension on one inch diameter stock. All material was normalized prior to straining for uniformity of test results.

Three measurements were taken on each specimen: energy absorbed, percentage cleavage fracture, and percentage expansion of the specimen back. A total of 234 specimens were tested over a temperature range from - 40° F. to + 100° F. to establish the complete transition curve for each strain condition. A summary of the normally defined transition temperatures is made for each strain condition.

Prestraining beyond the yield point increased the transition temperature. Prestraining below the yield point caused a slight improvement in impact properties particularily at higher levels of energy absorbed. Both the 15 foot pound transition temperature and the 50% Cleavage transition temperature were increased by an average of 3.5° F. for each 1% prestrain up to 9.7% prestrain with the rate of increase being slightly above the average for lower values of prestrain.

Good correlation was found to exist among the 15 foot pound transition temperature, the 50% Cleavage transition temperature and the 8% Expansion transition temperature. The use of the 8% Expansion transition temperature was found to have merit because of the ease of measurement.

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A. INTRODUCTION

The problem of brittle behavior in steel at low temperatures is of special concern to Canadian engineers. Today, this problem is becoming more acute as new techniques are developed and more construction is being done on a twelve month basis. In some industries such as oil drilling, winter is the only time heavy equipment can be moved in over the muskeg.

All industry has been affected by this problem either by actual damage, costly delays, or plain nuisance. In the construction industry alone, much difficulty has been experienced with hooks of reinforcing steel literally dropping off while handling during cold weather. This particular problem prompted the University of Alberta to investigate the effect of prestraining on the cold weather brittle behavior of steels.

One of the most spectacular instances of brittle failure of steel in the Edmonton area occurred late in 1955 during the construction of a power plant near Forestburg, Alberta. A heavy wide flange column of over 100 pounds per foot accidently fell and snapped into two pieces. The investigation concluded the failure was due to cold weather brittleness.

Dr. G. Ford of the University of Alberta related in discussions that difficulty was experienced in the construction of schools in the northern areas of Alberta. While handling the reinforcing steel during the winter, a large number of hooks broke off at the beginning of the hook bends. Investigation found the steel to be of Intermediate Grade conforming to ASTM Specification A-15 (1)*; however, the tensile properties were in the upper portion of the allowable range. The hooks were also bent on mandrels one size too small for the size of bar.

* Numbers in parenthesis refer to references in bibliography.

The Department of Highways, Bridge Branch, of the Alberta Government has had similar experience with reinforcing hook breakages. The bars fractured at the beginning of the hooks although there was no instance of incorrect radius of bending.

Mr. N. Blakey revealed in discussions that Dominion Bridge Co. Ltd. have encountered difficulties with hooks breaking off during cold weather steel placing operations. The trouble was with intermediate grade reinforcing bars which were high in carbon content, and as a result fell in the upper portion of the allowable range of tensile properties. The hooks always broke off at the beginning of the bends.

An interesting opinion of both the Department of Highways, Bridge Branch and the Dominion Bridge Co. Ltd. was that the temperature at which the bars were bent had an important bearing on the properties during cold weather. Both parties felt that bars bent while the steel was cold, compared to room temperature, showed a much greater tendency to be brittle than bars bent with the steel at room temperature.

Another example of cold weather brittle behavior of steel occurred during the construction of wooden grain cribs in 1957. Mr. T. Lamb of T. Lamb, McManus and Associates Ltd. related (2) that corner braces shaped in the form of an inverted U were found to break adjacent to the bends during placing. About 500 of some 6,434 rods broke at a temperature between 32 to 40 degrees F. "Normal physical tests carried out on the steel indicated that it was in the mild steel range but both the tensile strength and yield strength were fairly high".

Other examples (3,4) of brittle behavior concern the failure of lifting hooks at a Canadian Utilities, Limited power plant near Valleyview, Alberta. Two snatch hooks failed suddenly under load during construction

of the plant in 1957. A lifting eyebolt failed in a similar manner on a light piece of equipment during a routine inspection the following year. All three failures were attributed to a low temperature brittleness. In the case of the eyebolt, the 25 foot pound Izod transition temperature was above 100° F.

Doubtlessly, many more cases of steel failures in Alberta, due primarily to cold weather brittleness, could be cited.

Several of the examples given are for steels which had either been given a certain amount of prestrain or had been subjected to possible straining during their history. As an illustration, the reinforcing steel failures all occurred at the beginning of the hooks. Trouble was not experienced with the unstrained material.

The obvious question which arises when studying these failures is the extent that prestraining affects the cold weather properties of steel. It is this question that is dealt with in this work. A review of available technical literature on the subject is made, and a series of impact Charpy tests is performed on strained and unstrained material to obtain both a qualitative and quantitative partial answer to this question.

B. DEFINITION OF SPECIAL TERMS

Impact Energy: Impact energy refers to the amount of energy absorbed by an impact specimen broken in an impact test; also referred to as absorbed energy and impact value.

Shear Fracture: Shear fracture is a type of fracture surface associated with impact test specimens which have absorbed a relatively large amount of energy during testing. Shear fracture indicates "tough" behavior of the steel with a large amount of plastic deformation and is characterized by a "fibrous" appearance.

Cleavage Fracture: Cleavage fracture is a type of fracture surface associated with impact test specimens which have absorbed a relatively small amount of energy during testing. Cleavage fracture indicates "brittle" behavior of the steel with little or no plastic deformation and is characterized by a "bright crystalline" appearance.

Transition Range: The transition range is the range of temperatures in impact testing data over which some measured value such as energy absorption, ductility, or fracture appearance undergoes an appreciable change.

Transition Temperature; A transition temperature is a particular temperature chosen arbitrarily from the transition range for easy comparison of test data; sometimes referred to as the embrittling temperature.

Fracture Appearance Transition Temperatures: Fracture appearance transition temperatures refer to particular transition temperatures based on criteria which depend upon the mode of fracture and hence the fracture appearance. They indicate the manner a crack propagates through a material once started.

Ductility Transition Temperatures: Ductility transition temperatures refer to particular transition temperatures based on criteria which reflect the relative ability of a steel to flow plastically before extensive cracking

occurs. They are associated with the ductility of the metal at the notch apex and the change in fracture appearance of a small zone directly under the notch.

C. HISTORICAL REVIEW

1. Introduction

The Bessemer process of steel making was developed about 1856, and the open hearth process was developed about 1861. Shortly thereafter, steel became available in comparatively large quantities, and thus gradually replaced wrought iron as a structural material. An early recorded mention of the brittle failure problem of steel appeared in the Journal of the British Iron and Steel Institute for 1879. (5) Therefore, the history of brittle failure of steel in engineering structures extends back to virtually when steel first became generally used as a structural material.

It was not until the failure of ships at sea and at dockside during World War II that the problem of brittle fracture was brought into sharp focus. (6) Since that time, much has been done to understand the problem better. Even though the knowledge in this area has advanced tremendously, it is still inadequate to permit the preparation of a satisfactory engineering design textbook on the subject.

As a background to the work of this thesis, an attempt is made here to summarize the effects of various factors on the brittle behavior of steel. This information has been taken from the technical literature available on the subject.

Primary factors (7) influencing the brittle behavior of steel are temperature, structural discontinuities, and steel manufacturing variables.

2. Effect of Temperature

When standard unnotched tension specimens of low carbon structural steel are tested at the temperature of liquid nitrogen, they are found to be extremely brittle. Normal ductile behavior is exhibited by specimens broken at temperatures above about 200° F., but below this temperature the

steel, undergoing an abrupt change in characteristics, becomes extremely brittle. These properties are typical of hot-rolled carbon structural steels. (7,8)

The effect of testing temperature on the impact energy of notched impact specimens of ferritic steels is well known. There is a range of temperature in which the impact energy suddenly decreases, and the fracture appearance changes from "fibrous" to "bright crystalline". (7,8,35)

3. Effect of Notches

Parker has demonstrated (7) that the dual behavior of steel is the result of its ability to fracture by either of two modes: shear or cleavage. Shear fractures follow planes of maximum shear stress on a macroscopic scale; cleavage fractures follow planes of maximum tension. The nature of the stress system is of major importance in governing the behavior of steel. When the ratio of maximum shear stress to maximum tensile stress is high, ductile behavior and shear fracture mode are to be expected. When the reverse is true, brittle behavior may be anticipated. Notches, producing triaxial tension stresses, (8) increase the ratio of tensile to shear stresses.

The stress-raising effect of a notch, however, is not the primary cause of trouble. (6,7) When sharply notched specimens are made geometrically similar and are tested at various temperatures, the thicker ones break in a brittle manner at ordinary room temperatures, while the thinner ones remain ductile even at much lower temperatures. This effect of plate thickness can be explained qualitatively. A sharp notch introduces a complex state of stress with tensile components acting in both the thickness and width directions. The stress acting in the thickness direction depends upon the plate thickness.

In summary, a sharp deep notch not only acts as a stress raiser, but greatly alters the state of stress locally. Uniaxial or biaxial tensile loading of a specimen containing a notch may thus create a local state of triaxial tension with a consequent lowering of the ratio of maximum shear stress to maximum tensile stress. The sharper and deeper the notch and the thicker the plate the lower is this ratio, and consequently the greater the expectation of brittle behavior.

4. Manufacturing Variables

Manufacturing variables can be divided into two sections: those which are related to variations in treatment, and those associated with variations in chemical constituents. Under variations in treatment fall such items as grain size, welding, cold work and strain aging, heat treatment, and rolling procedure. Each of the manufacturing variables will be considered in turn.

(a) Effect of Grain Size

The ferrite grain size generally has a marked effect on transition temperature, but the magnitude of the effect varies with the manufacturing and heat treating practice. (6) The smaller the ferrite grain size, the lower the transition temperature in a given test. The ferrite grain size depends upon the final rolling temperature and the rate of cooling from above the transformation temperature. Hot-rolling practice thus has a predominant influence in establishing the grain size. Low finishing temperatures and fast cooling favor the formation of small ferrite crystals. Thinner plates normally cool faster than thicker ones, and hence have a more favorable grain structure.

(b) Effect of Welding

Defective welding has played a major role in initiating brittle behavior in large structures. Weld defects are common because the

numerous variables in welding are difficult to control. Weld defects provide notches which have the capacity of transforming uniaxial stresses into dangerous triaxial tensile stresses.

The problems of weldability can be classified into two groups:(6) those of making sound welds, generally referred to as joinability; and those of serviceability, dealing with the mechanical performance of the weldment. Serviceability is governed by the same factors which affect the quality of rolled plates. The basic factors are: (1) chemical composition, (2) microstructure, and (3) structural discontinuities.

Welding also introduces residual stresses in a structure: Whether or not such stresses can or do contribute to brittle behavior of large structures is still a subject of debate. (6)

Scotchbrook et al (9) after investigating the effect of welding on pressure-vessel steels concluded that welding appreciably increased the notch sensitivity of plate and that this increase could not be predicted from the transition temperature characteristics of unwelded plate.

The following conclusions were made by Shank (5) concerning the role of welding in brittle behavior: (1) Brittle behavior can cross riveted joints; (2) There is no evidence to show that the percentage incidence of brittle failure has either decreased or increased with the welding; (3) Residual stresses are not the prime cause of brittle failure, but such stresses may, in conjunction with other factors, initiate such failure; (4) Except in the case of exceptionally poor welds, there is no tendency for fracture to follow welded seams.

(c) Effect of Cold Work and Strain Aging

It has been repeatedly shown (6) that cold working, even without aging, may raise both the fracture appearance and ductility transition temperatures.

However, cold work plus aging is more effective in raising the transition temperatures of hot-rolled structural carbon steel than is either cold work or aging alone.

Reference is made by Kenyon and Burns (10) to work by Bauer who cold worked pieces of boiler plate 16% by a special compression tool. The cold working reduced the impact value in one case from 10.9 to 1.7 meter kilograms per square centimeter.

Kenyon and Burns also show curves of "Notch Toughness Mkgm per square cm. vs. Temperature degrees C." for Iron-Nickel-Titanium Alloys which had been "Not Cold Worked" and "Cold Worked and Aged two hours at 100° C.". Cold working and aging increased the temperature for equivalent values of "Notch Toughness". There also was a reduction in the maximum notch toughness of the cold worked material.

In the same paper, Kenyon and Burns refer to work by Greaves and Jones who investigated the effect of temperature (approximately -100° C. to 700° C.) on impact strength. A graph with three curves is shown with "Impact Figure in Kgm vs Temperature °C" for three samples of 0.17% C. mild steel. These were hot rolled, cold rolled 16%, and cold rolled 33%. Two effects are noted for the range from -100° C. and +100° C.:

(1) The straining reduced the highest impact value of the hot rolled material by almost one-half for the 16% strain and approxiamtely one-third for the 33% strain condition, and

(2) The two curves for the strained material were shifted to a temperature of +50° C. above the hot rolled curve.

The slopes of the three curves appear almost the same and the position of the curves for the strained material are almost one on top of each other, particularily for the lower values of impact value.

Stout and McGeady (11) investigated the effects of straining and aging, among other things, on the notch sensitivity of welded steel plate. For 1/2 inch 0.20% C. silicon killed plate, the fracture transition (50% shear failure) was raised by both straining and aging. The same was true for the ductility transition (per cent lateral contraction).

Osborn et al (12) describe work at Lehigh University on the effect of plastic strain and heat treatment on carbon steel. Two heats of carbon steel were given varying cold forming treatments from no prestrain to 10% prestrain followed by varying heat treatments from no treatment through accelerated strain aging and stress relieving to normalizing. Three criteria were used, namely, total energy absorbed, per cent cleavage in fracture surface, and per cent lateral contraction. The transition temperatures by all three criteria were raised for each steel. In the killed steel, the transition temperature was raised about 20° by the 1% tensile strain. Increasing strains continued to raise the transition temperature resulting in a total rise of about 50°. The transition temperature of the rimmed steel, however, was immediately raised about 60° by the 1% strain, while further straining had little effect. The only post heat treatment which appreciably lowered the transition temperatures was normalizing.

Scotchbrook et al (9) give the results of a study using the Lehigh slow notch-bend test to determine the effect of welding on as received and prestrained plate. Five per cent prestrain was produced by stretching plate 9-1/2" wide by 16 feet long. Gauge marks were scribed at 2 feet intervals. A 2 foot section from each end was discarded for end conditions. Measurements were made of per cent lateral contraction, per cent cleavage, and per cent energy absorbed. It was concluded that welding prestrained

material resulted in transition temperatures slightly higher than for welding unstrained plate.

Kinzel (13) demonstrated that straining raises the embrittling temperature. It was concluded that "this is not strange as total plastic deformation is not unlimited, and prior straining uses some of it. The effect of a small amount of prior strain is of major consequence only in the less ductile, high carbon steels".

Tör et al (14), using the Lehigh slow-notched-bend test, concluded that a tensile strain of 20% parallel to rolling raised the ductility transition 80° F. above the unstrained steel. This was 35° F. above the transition temperatures of earlier tests given 5% strain. It was also found that steels strained 20% transverse to the rolling direction had transition temperatures 130° F.higher than unstrained material.

Tipper (15) has stated that previous cold work will make steel more susceptible to cold brittleness, particularily if it is subject to strain-aging, and that this is true of all semi-killed steels. Tipper(16) investigated the effect of direction of rolling, direction of straining, and aging on the mechanical properties of a mild-steel plate. The direction of rolling was found most significant in the Izod impact tests with the specimens taken across the direction of rolling yielding the lower maximum values of energy absorbed. The low values of energy absorbed did not appear to change greatly. The first effect of prestrain on Izod test results was to lower all the values of energy absorption, particularily in the transition range. At the same time, partly crystalline fractures were obtained at higher temperatures. Tipper concluded, "The lowering of values of impact following prestrain would appear to be chiefly due to work-hardening and strain-aging, which affect both directions of rolling equally." This conclusion differs from that of Tör et al. (14)

Vanderbeck and Gensamer (17) tell of numerous Charpy keyhole-notched impact tests on strained and unstrained specimens of various steels performed by the Carnegie Illinois Steel Corporation. All results showed that straining raised the temperature of the ductility transition and moreover that it was raised more for some steels than for others. Whereas there was 100° F. difference between the fracture transition temperature and ductility transition temperature in the case of the as rolled material, after straining 10% by cold rolling, the fracture transition temperature was often the same or only slightly above the ductility transition temperature. The authors concluded, "Straining raises the ductility transition considerably and the fracture transition very little if not at all."

Wright (18) has shown that cold deformation in tension will raise the transition temperature and that if the impact energy at a constant temperature is plotted as a function of the amount of cold deformation, it too, will show a transition. That is, the energy absorbed will drop to a lower plateau after a certain amount of straining. This fact is also illustrated by Parker. (6)

Ripling (19) in a series of investigations, showed that under certain circumstances straining can actually improve the ductility of steel. Ripling stated, "It is generally thought that any metal which does not crystallize in the face centered cubic system will exhibit a rather narrow testing temperature range (the transition temperature) over which it abruptly changes from ductile and tough to brittle. It has been shown that this ductility (and presumably the toughness) deficiency at subtransition temperatures can be cured, partially at least, by cold working the metal at a supertransition temperature before testing it at

the subtransition temperature. This portion of low temperature brittleness which is strain curable is labeled 'Rheotropic Brittleness'."

As a summary of the literature available on the effect of prestrain on impact strength, the following conclusion could be made:

1. Straining may raise both the fracture appearance and the ductility transition temperatures, although the ductility transition temperature may be affected to a greater degree.
2. The effect of straining on raising the transition temperature is greater on some steels than on other steels.
3. The effect of cold work plus strain aging is more effective in raising the transition temperature than is either straining or aging alone.
4. The effect of straining and aging may or may not affect the transition temperatures of both directions of rolling equally, apparently depending on the test used.
5. If the impact energy at a constant temperature is plotted as a function of the amount of cold deformation, it too, will show a transition.
6. In some steels ductility deficiency at subtransition temperatures can be cured, partially at least, by cold working a slight amount at a supertransition temperature.

(d) Effect of Chemical Composition

There have been very few comprehensive investigations on the effect of variations in chemical composition on transition temperatures of hot rolled structural carbon steel. (6) There is some data available however, and even though there is lack of agreement on some details, the general effects of composition seem fairly clear.

Carbon:

"Carbon plays a dominant role; it is the most important single factor in determining the level of the embrittling temperature." (13) Rinebolt and

Harris (20) illustrated the effect of varying carbon contents on four different transition temperatures as determined from V-notch Charpy tests. The 15 foot pound transition temperature was raised 17.5° F. for each additional 0.1% of carbon for carbon contents between 0.0 and 0.4%, and 85° F. for each additional 0.1% C. for carbon contents between 0.4 and 0.8%. The average energy transition was raised 48.7° F. for each additional 0.1% carbon content. The 50% cleavage transition was raised 56.4° F. for each additional 0.1% C., and the first sign of cleavage was raised 65° F. for each additional 0.1% carbon.

Lorig (21) determined the effect of carbon on the 50% fibrous fracture transition temperature for the Kahn (Navy) tear test. The results are for hot-rolled semikilled pearlitic steels. The effect of carbon was to increase this transition temperature about 30° F. for each 0.1% increase in the carbon content.

There is some evidence that the transition temperature for high purity iron is not affected by the first 0.01% of carbon added, however, with greater amounts of carbon it rises sharply to values considerably above room temperature. (21)

The addition of carbon affects the shape of the temperature-energy curve. (6,22) With carbon contents of less than 0.01%, the maximum energy absorbed by a specimen is at a maximum value and the temperature range over which the energy falls off is very narrow. With the addition of carbon the maximum energy decreases rapidly and the temperature range over which the transition occurs becomes quite broad. That is to say, the slope of the transition portion of the temperature-energy curve decreases with increase in carbon content. This accounts in part for different effects on the different transition temperature criterions when the carbon content is varied.

Manganese

"Manganese lowers the 50% fibrous fracture tear test transition temperature 4° F. or less for each 0.1% increase in manganese content. Manganese was found to have a greater effect on both the 10 foot pound and the 20 foot pound keyhole Charpy transition temperatures, lowering each about 7° F. for each 0.1% increase in manganese content." (6) The effect of manganese is affected by the ferrite grain size.

Rinebolt and Harris (6,23) found that for fully killed steels the average energy transition temperature for V-notch Charpy specimens was lowered about 10° F. for each 0.1% increase of manganese. The ductility transition temperature (15 foot pound) for V-notch Charpy specimens was also lowered about 10° F. for each 0.1% increase in manganese content; the results would have been substantially the same for a 10 foot pound ductility transition.

Boulger et al (24) state that replacing 0.01% carbon with sufficient manganese to maintain the same tensile strength lowers the 20 foot pound Keyhole Charpy transition temperature about 10° F.

Silicon

The evaluation of the role of silicon is complicated by the fact that silicon acts as both a deoxidizer and an alloying element. The action of silicon will hence depend on the concentration of other deoxidizing elements such as manganese and aluminum. (6) Silicon is beneficial as long as it is acting as a deoxidizing agent but detrimental once the steel is fully deoxidized after which the silicon acts as an alloying agent.(24)

Rinebolt and Harris (6,23) investigated the properties of laboratory heats of fully deoxidized steels, within the range of 0.2 to 3.0% silicon the 50% cleavage area transition, the average energy transition

and the 15 foot pound transition all rose at a rate of 13° F. for each additional 0.1% silicon.

Phosphorus

"This element increases the various transition temperatures at a rate that equals or exceeds that of carbon. The effect varies slightly with the manganese content of steel." (6)

Boulger et al (24) determined the effect of increasing the phosphorus content of semi-killed steel plate from 0.01 to 0.06%. Data would indicate that each increase of 0.01% phosphorus will raise the 20 foot pound Charpy transition temperature 8° F.

Sulfur

Parker (6) states, "The meager results available indicate that sulfur has little, if any, effect upon the ductility transition temperature."

Boulger et al (24) indicated that data on steels containing 0.023 to 0.050% sulfur but otherwise of the same composition showed sulfur to have no effect on either the Charpy or tear test transition temperatures.

Nitrogen

The effect of nitrogen varies with the manganese and carbon contents.(6) In one series of tests the V-notch Charpy average energy transition was increased about 20° F. by the addition of 0.005% nitrogen for the low manganese steels and 35° F. for the high manganese group. The same change in nitrogen, however, had no influence upon the 10 foot pound transition temperature (ductility transition) for the low manganese steels and increased the ductility transition temperature for the higher manganese steels by only 20° F.

Oxygen

Oxygen plays a complex role in steel because of its reactions with iron and other elements present.(6) Oxygen is known to have a detrimental

effect upon the toughness and ductility of low carbon steel, however, the quantitative effects are not exactly known.

Aluminum

Aluminum modifies the embrittling effect of oxygen; it alters the structure of sulfide inclusions, and it tends to combine with nitrogen. (6)

Boulger et al (24) found aluminum additions to semi-killed steel was generally effective in decreasing transition temperatures, however, the effect was not uniform and varied with silicon content.

Nickel

Nickel is recognized as being beneficial. (6) Both fracture appearance and ductility transition temperatures decrease progressively with increasing nickel content. Nickel becomes increasingly beneficial until at 13% nickel there is no transition from ductile to brittle behavior even at temperatures as low as -300° F.

Titanium and Zirconium

Titanium above 0.04% increases the transition temperatures. (24) In amounts up to 0.04% zirconium did not markedly affect the transition temperatures. Charpy tests indicate slightly larger quantities of zirconium might be beneficial since it is a strong deoxidizer.

Vanadium and Molybdenum

Small amounts of molybdenum or vanadium under 0.10% apparently do not influence the transition temperatures. (24) When the vanadium content was increased from 0.10 to 0.20% the transition temperature was raised 80° F. Vanadium is being used to impart nonaging properties to rimmed steels.

Summary of Effects of Chemical Composition.

Table 1 gives a summary of the effects of various elements upon three definitions of transition temperatures for V-notch Charpy specimens.

TABLE 1

SUMMARY OF EFFECTS OF CHEMICAL COMPOSITION ON TRANSITION TEMPERATURE

(Adapted from Table - Page 185 Parker (6))

Approximate Change in Transition Temperatures Produced by Various Elements

Increase In Element	Average Energy Charpy V-Notch	15 Ft. Lb. Charpy V-Notch	10 Ft. Lb. Charpy V-Notch
0.1% C.	Approx. + 50° F.	+ 17.5° (0 to 0.4% C.) + 85.5° (0.4 to 0.8% C.)	+ 20° F.
0.1% Mn.	- 10	- 10	- 10
0.1% Si. (0.2% Max.)	Beneficial when acting as a Deoxidizing Agent		
0.1% Si. (0.3% Min.)	+ 13	+ 13	+ 13
0.01% P.	+ 15	+ 13	+ 11
0.01% N. (about 0.45% Mn.)	+ 40	no data	0
0.01% N. (about 0.75% Mn)	+ 70	no data	+ 40
1.0% Ni.	- 10	- 35	no data
S. (0.06% Max.)	0	0	no data

Note: + indicates increase; - indicates decrease.

D. The Meaning of Transition Temperature

In this section some of the conclusions concerning the meaning of transition temperature as related to impact test data will be summarized.

Many different types of laboratory tests have been developed to study the impact properties of steels. (6) The test specimens have ranged in size from the small conventional Charpy specimens to full scale specimens up to 6 feet across and weighing more than a ton. The cost of the latter specimens, of course, places a severe limitation on the number that can be made and tested. Notch toughness tests are conducted at various temperatures to determine the temperature range over which an appreciable change takes place in some measured value such as energy absorption, ductility, or fracture appearance.

In any particular test specimen, a change in the measured value frequently occurs rather abruptly as evidenced by a drop, for example, from a relatively high energy absorption to much lower energy absorption at some lower testing temperature. When this type of behavior is observed, it has been found the change does not occur at a single temperature but rather over a temperature range. This range is usually referred to as a transition range. (6) Frequently there is appreciable scatter of the data in this range as is evidenced by typical data of the standard keyhole Charpy impact test. For some specimens the transition range does not have appreciable scatter, rather, the change is quite gradual and uniform. Typical V-notch Charpy data is an example of this latter behavior.

It has been usual practice in the past to select some particular temperature chosen arbitrarily from the transition range and to call this the transition temperature. This allows quick and easy comparison

of data. The value of such comparisons is very useful but necessarily limited since such a transition temperature does not give any indication of many features of the transition curve. For example, the transition temperatures of two steels could be the same and yet the slope, the scatter, and the maximum and minimum values of the two transition ranges be quite different. The difficulty encountered is akin to reducing a two and possibly three dimension problem to a single point.

When a multitude of test methods and specimens are imposed upon the above limitation, it becomes readily apparent why it has been so difficult to make comparisons of different test data.

There has emerged a theory which to some extent has assisted in interpreting impact test data. It is suggested that the choice of test specimen is far less critical for the correlation of test data than is the choice of the criterion used to establish the transition temperature. The criteria of transition temperature may be roughly divided into two groups. (6) Those in one group depend upon the mode of fracture and hence the fracture appearance. These criteria depend upon the way in which a crack propagates through the specimen and are a measure of what is commonly called a fracture appearance transition temperature (sometimes called the fracture transition). Those in the second group presumably reflect the relative ability of a steel to flow plastically before extensive cracking occurs. These criteria are concerned with the ductility of the metal at the notch apex and are used to determine what is commonly called a ductility transition temperature.

To explain the two types of transitions more fully, in notch test specimens a change in fracture appearance from a fibrous to a granular fracture occurs over a certain temperature range as the testing temperature is lowered. The temperature at some arbitrary point within this

range maybe called the fracture transition temperature. A drop in the total energy absorption also occurs over the transition range but in many types of test specimens the energy absorbed at the temperature at which predominantly granular fracture is obtained is still appreciable. In this event as the temperature is lowered still further the energy absorbed continues to decrease. For some specimens and for some steels a point is reached at which the energy absorbed drops suddenly to an extrememly low value. This latter drop may be called the ductility transition temperature. (17)

The ductility transition is associated with the change in fracture appearance of a small zone directly under the notch. (17) The little shear area at the notch apex is sometimes referred to as a "thumbnail". (6)

The fracture appearance transition occurs at a higher temperature than the ductility transition. (6) Under certain conditions, the two transitions may occur at the same temperature, but the fracture appearance transition never occurs at a lower temperature than that of the ductility transition. This is a consequence of the observed physical behavior of the specimens and the manner in which the two transitions have been measured.

In the temperature range between the ductility and fracture appearance transitions, the properties vary continuously. It therefore is possibleto select criteria which would give a combination of the two transitions.

Several criteria maybe used to determine each transition temperature. In order to determine the transition which is desired, whether fracture or ductility, care should be exercised in the selection of such criteria and the evaluation of test results. Failure to do so may result in

apparent anomalies when the results of different types of specimens are compared. (17)

Some transition curves such as the Temperature-Energy curve of V-notch Charpy data do not exhibit any abrupt ductility or fracture appearance transitions. In such cases, the criterion for the ductility transition temperature must be arbitrarily chosen and should be selected so that the transition actually represents the change to almost completely brittle behavior. The ductility transition temperature for the V-notch Charpy curve should therefore be selected near the bottom of the curve, say at 10 or 15 foot pounds. (6) A fracture appearance transition temperature may be arbitrarily selected where the fracture appearance is 50% fibrous.

In general, ductility transition temperatures are sensitive to variations in notch geometry, specimen shape, and rate of loading. Faster rates of loading, changes in notch geometry that increase the notch acuity, and increase in specimen size all raise the ductility transition temperature. In some specimens welding also raises the ductility transition temperature. Fracture appearance transition temperatures, however, are relatively insensitive to these factors. The fracture transition is raised if the straining is sufficient to raise the ductility transition above the fracture transition of the unstrained material. With sufficient straining the ductility and fracture transitions occur at very nearly the same temperatures. (6,17)

The ductility transition rather than the fracture transition is believed to correlate more closely with actual performance in structures. (17) As mentioned previously, the ductility transition is associated with low energy absorption in the V-notch Charpy test. (6) Fractured

plates from ships which have failed in service usually exhibited small reductions in thickness in the order of 1%. It is logical to associate the behavior of these fractured plates with low energy absorption and thus to look for similar performance at low energy levels in the impact or any other tests. (17,13)

Correlations have been made between the ductility transitions of two different tests, the V-notch Charpy test and the Keyhole Charpy tests. (17) The correlation was found to be quite good. It has been suggested that much of the difficulty in the past, when making comparisons of test results, was due to indiscriminate mixing of the test data.

In summary, it would appear that there are two transition temperatures with meaning: the ductility transition and the fracture transition. The ductility transition appears to be the transition associated with the initiation of a crack whereas the fracture transition is more closely associated with the propagation of a crack once started.

E. EXPERIMENTAL PROCEDURE

1. Introduction

As outlined in the introduction to this thesis, there have been several instances of brittle behavior of mild steel in the Edmonton area where the steel had either been given a certain amount of prestrain or had been subjected to possible straining in its history. This factor of prestrain is investigated by a series of Charpy impact tests to determine the extent that prestraining affects the cold weather strength of a mild steel.

2. Specimen Preparation

(a) Material

The material for this series of tests was purchased from a commercial steel supply company. A total of one hundred and sixty feet of one inch diameter plain round bar in forty foot lengths was required. Each forty foot bar was cut into ten, four foot lengths and bundled separately.

Composition of Bars

The steel was manufactured by Premier Steel Mills of Edmonton to conform in general to AlSl 1015 Steel. The bars were all of Mill Heat Number 5711. The ladle analysis of this particular heat number is listed in Table 2.

Table 2

Ladle Analysis of Heat 5711

Carbon Content	0.14%
Silicon Content	0.12%
Manganese Content	0.45%
Sulfur Content	0.47%
Phosphorus Content	0.016%

In order to check the uniformity of the steel purchased, a carbon analysis was performed on each of the forty foot bars by Hanson and Parr Engineering Limited. One sample was taken from each forty foot bar in a random manner. Results of these analysis are shown in Table 3. Each sample was divided in two; and analysis was made on each half, and the average of the results taken.

Table 3

Carbon Analysis of Forty Foot Bars

Bar	Sample A	Sample B	Average
1	0.168%	0.166%	0.17%
2	0.144	0.145	0.15
3	0.166	0.162	0.16
4	0.166	0.168	0.17

A complete chemical analysis of heat 5711 was also done on an additional sample taken from one of the bars. The results of this analysis is shown in Table 4.

Table 4

Analysis of Steel Sample - Heat 5711

Carbon	0.132%
Silicon	0.14
Sulfur	0.036
Manganese	0.389
Phosphorus	0.016
Chromium	0.069
Nickel	0.108
Molybdenum	0.026

Since the carbon content shown in Table 3 was fairly consistent, no further consideration was given to keeping the bars separated. The material for testing was chosen at random from the one hundred and sixty feet of stock.

Mechanical Properties of Bars

Tensile tests of the normalized bars were made in accord with ASTM Specifications (25) on three Type 1 standard round tension test specimens. The specimens were pulled in the Baldwin Universal Testing Machine shown in Figure 1. The Micro Former attachment was used to obtain a stress strain curve of each specimen. One of these stress strain curves is reproduced in Figure 2.

The results of the tension tests are listed in Table 5. The modulus of elasticity of the material was determined by using SR_4 strain gauges employed in further testing described in a later section.

Table 5

Mechanical Properties of Normalized Bars

		Specimen			
		1	2	3	Average
Upper Yield Stress	ksi	-	41.5	-	-
Lower Yield Stress	ksi	35.7	36.4	36.4	36.2
Ultimate Tensile Strength	ksi	56.9	56.4	57.5	56.9
Elongation 2" gauge	%	42%	41%	41%	41%
Reduction in Area	%	68.8%	70.0%	68.2%	69.0%
Modulus of Elasticity	ksi	-	-	-	30.0

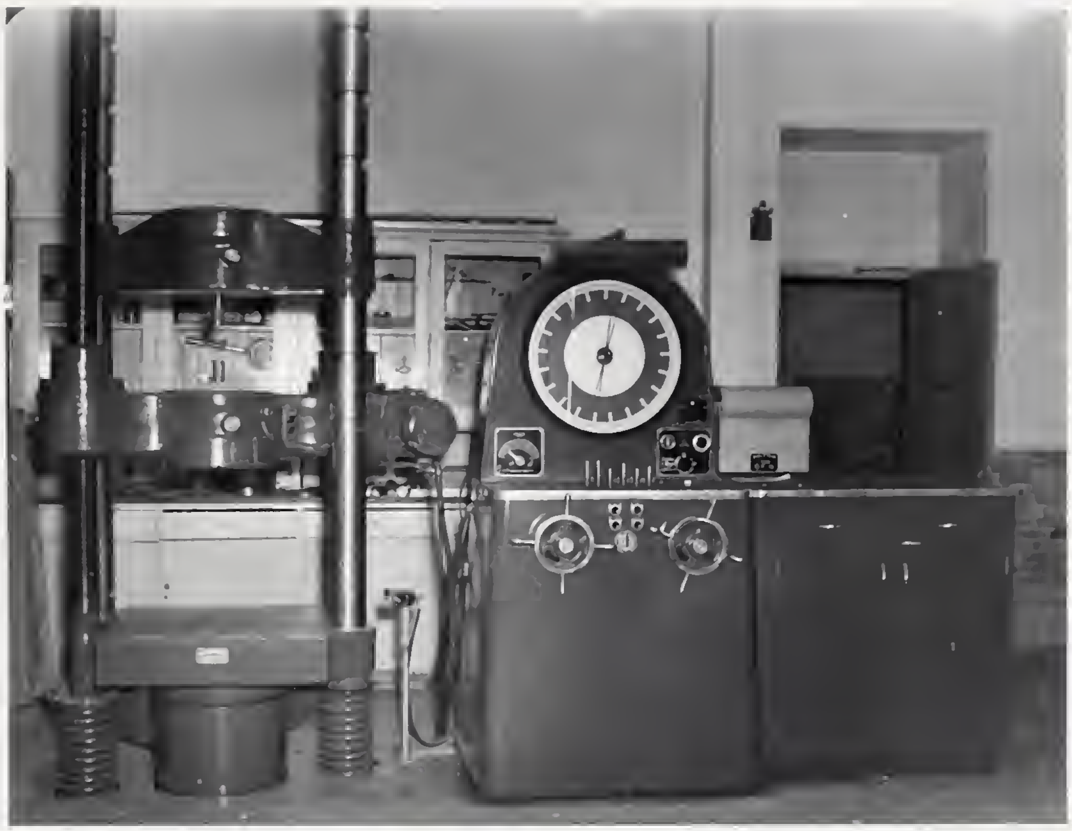

Figure 1

200,000 Pound Baldwin Universal Testing Machine

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(b) Heat Treatment of Bars

The material used in the tests was all normalized to assure a uniform strain condition. This was done on the advice of Dr. J. G. Parr of the Department of Mining and Metallurgy, University of Alberta. The effect of normalizing on steel is covered in most tests on metallurgy.(8) In this particular case, normalizing was employed to relieve possible internal stresses induced by some previous treatment such as rolling or uneven cooling and to bring the material to a uniform strain condition.

The material was heated to 1675° F. in a commercial heat treating furnace and held at that temperature for one hour. The entire one hundred and sixty feet of bar was done at one time. After the hour the bars were removed from the furnace and cooled in still air. The heat treating was done on March 5th, 1959.

(c) Straining of Bars

Strain Conditions

The following is a list of the Strain Conditions used in these tests:

Strain Condition 1 - In normalized condition.

Strain Condition 2 - No measurable prestrain. (Strained just below yield point.)

Strain Condition 3 - 2.5% Prestrain.

Strain Condition 4 - 4.9% Prestrain.

Strain Condition 5 - 9.7% Prestrain.

Apparatus for Straining

All straining of the bars was done on the Baldwin Universal Testing Machine shown in Figure 1. Bars for Strain Conditions 3, 4 and 5 were strained in 4' -0 lengths with mill scale unremoved. Bars for Strain Condition 2 were machined clean and were strained in lengths of approximately 2' -0.

All straining was done at a rate of approximately 5000 pounds per minute.

Measurement of Strain

Several different methods of measuring the strain were employed depending on the amount of strain desired. It was found impossible to obtain a uniform strain between the first initial yielding and approximately 2.5% strain. This is discussed in greater detail in a later section.

A series of four 8 inch gauge pock marks on each side along the length of the bars were used to measure strain in Strain Conditions 3, 4, and 5. By measuring both the overall distance and adjacent distances of pock marks with a steel tape, a check on the uniformity of strain was made.

For Strain Condition 2, the loading of the bars was controlled by calculated load and not by amount of strain, although the strain was checked by gauge marks.

Accuracy of Measurement of Strain

The distance between pock marks was measured to the closest 1/64 of an inch. This means for an eight inch gauge distance the measurement was accurate to ± 0.20% of strain. For a 32 inch gauge length the average strain was accurate to ± 0.05% of strain.

Non-uniformity of Strain -0 to 2.5% Strain

As mentioned previously, it was not possible to strain this particular material uniformly for strains between the yield point and approximately 2.5% strain. The reason for this difficulty is open to speculation, however, it is likely associated with the stress strain characteristics of mild steel. A reproduction of the stress-strain curve as recorded by the Baldwin Micro Former attachment during the tension tests is shown in Figure 2.

Initially, it was the intention of using 0.5% to 1.0% strain as one condition of prestrain. Several attempts to obtain this strain were made on the bars in the normalized condition. It was soon noted that whereas a 1% average strain could be measured on the overall gauge marks there was no strain whatever indicated in the center of the bar. The mill scale would also begin to drop off the bar in some sections only, usually near the top or bottom close to the chucks.

The first suspicion was that localized yielding was occurring due to variations in the diameter of the rolled bar or variations in the effect and thickness of the mill scale. To eliminate the effect of these factors, two bars were machined clean of the mill scale to 0.750 ± 0.001 inches and 0.749 ± 0.001 inches in diameter and fitted with SR$_4$ strain gauges (see Figure 3). A total of six gauges plus a dummy gauge were used on each bar. On subsequent loading, it was shown that plastic yielding within the bar started at each end close to the chucks and proceeded from there to the middle of the bar. Once the yield point was reached at the location of a particular gauge, that same point would continue to yield until a permanent strain of more than 2.0% was attained. In the meantime there would be no further change in any of the other gauges.

The SR$_4$ gauges became inoperative by opening up after a strain in the order of 2.3%.

In the case of loading the first bar mounted with SR$_4$ gauges, upon reaching the yield point two gauges opened simultaneously. After reducing load and reloading, another two gauges opened. This sudden opening of gauges was unexpected and therefore a second bar mounted with SR$_4$ gauges was prepared. In view of how quickly yielding occurred at a strain gauge, greater care was exercised in loading the second bar. A diagram showing

gauge locations and numbering on the two bars is shown on Figure 3. Beneath each diagram is listed the amount of residual strain at each gauge after testing. It is interesting to note that in the case of the second bar there is a difference of 2.3% residual strain between two adjacent gauges numbered 17 and 19. The data recorded during the loading of the two bars are listed in Tables 6 and 7.

These tests indicate that straining in this type of material does not occur uniformily along the length of the bar in the strain range 0% to 2.5%. The first effects of strain hardening appear at approximately 2.5% prestrain. (See Figure 2.) The mill scale also drops off at a strain close to 2.5%.

In 1952 Tipper (16) investigated certain effects, including straining, on the mechanical properties of mild steel plate. It is stated that large test pieces of full plate thickness (0.51 inches), 18 inches long by 3 inches wide were marked in 2 inch lengths by fine scribed lines and "were then extended until yield had taken place throughout the parallel portion. The overall extension in the first two bars tested was found to be 3.75% after removal of load."

From this statement Tipper also apparently found that straining was not uniform until a certain strain had been reached.

Uniformity of Strain - 2.5% and Above

Once the whole bar had strained to the strain hardening zone, the strain was found to be quite uniform throughout the length. As mentioned previously, the uniformity of strain was checked by comparing the strains of successive 8 inch gauge lengths.

In one case the variation found between adjacent 8 inch gauge lengths was 0.37% strain. Usually the variation was less than 0.20%

strain in any one bar. This finding is also confirmed by the experience of Tipper (16) on similar material where it was found that differences over successive 2 inch gauge lengths were within 0.5%.

Choice of Strain Conditions of Tests

In choosing strain conditions for these tests, it was decided to select a range of strains normally encountered in the bending of concrete reinforcing bars. The strain at the surface of bars bent in accord with the recommended standard practice of the American Concrete Institute (26) varies from 5.9% for number 8 to 11 bars bent to a standard 180° hook to 9.1% for a minimum 180° hook. It was therefore decided to test material with prestrain conditions varying from zero strain to 10.0% strain.

A condition of no measurable prestrain was also chosen. The bars were loaded to a point just below the yield point then the load removed before any actual yielding had occurred. One reason for choosing this strain condition was to provide information as to why reinforcing hooks were breaking off immediately adjacent to the bends.

Loading Bars for Strain Condition 2

No Permanent Prestrain

The bars for this strain condition were all machined clean of mill scale to tolerances of ± 0.001 inches. The diameter of the finished bars were carefully measured and the load calculated which would give a unit stress of 35.5 ksi. This stress was chosen as a safe value below the yield stress determined from the tension specimens. (See Table 5.)

No difficulty was encountered in loading these bars. In each case no measurable change took place between gauge marks.

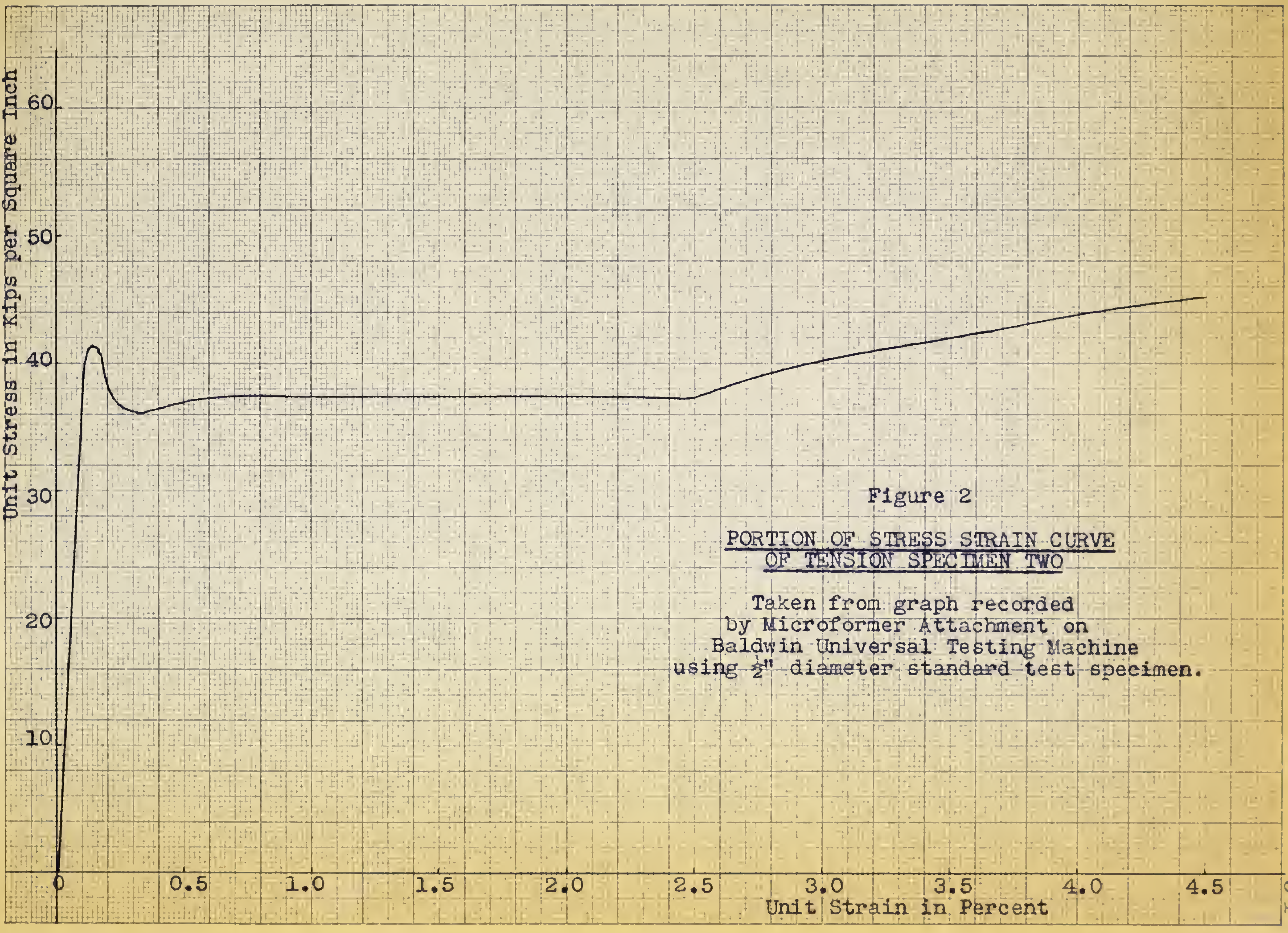


Figure 2

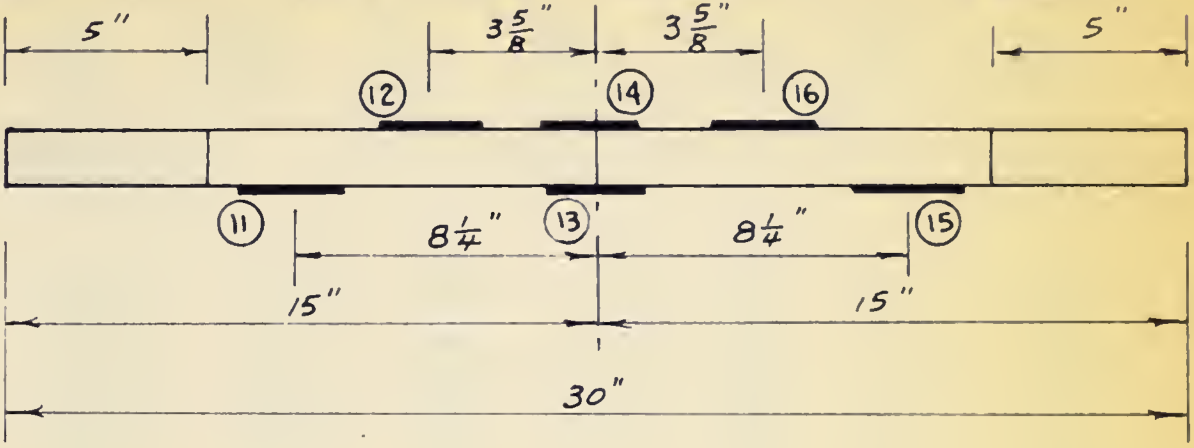
PORTION OF STRESS STRAIN CURVE
OF TENSION SPECIMEN TWO

Taken from graph recorded
by Microformer Attachment on
Baldwin Universal Testing Machine
using ½" diameter standard test specimen.

Figure 3

Diagrams Illustrating Bars Mounted With SR4 Strain Gauges And Summary of Residual Strains

FIRST BAR: Not drawn to scale. Dimensions to closest 1/16 of an inch unless noted.
Diameter: 0.750 ± 0.001 inches. Shaded portion in grips.

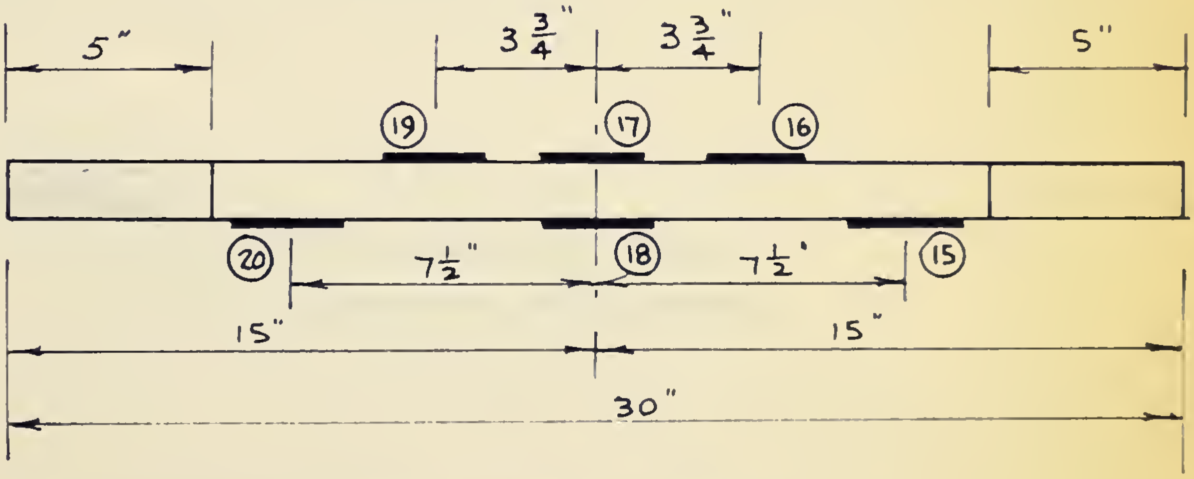


Residual Strain After Loading First Bar

At Gauge	11	12	13	14	16	15
Strain %	N 2.5%	2.0%	1.9%	N 2.5%	N 2.5%	N 2.5%

Gauges 11 and 16 opened first.
N Estimated value (gauge opened).

SECOND BAR: Not drawn to scale. Dimensions to closest 1/16 of an inch unless noted.
Diameter: 0.749 ± 0.001 inches. Shaded portion in grips.



Residual Strain After Loading Second Bar

At Gauge	20	19	17	18	16	15
Strain %	N 2.5%	2.3%	0.02%	0.7%	2.1%	N 2.5%

Gauge 20 opened first.
N Estimated value (gauge opened).

TABLE 6

STRAINS MEASURED ON LOADING FIRST BAR MOUNTED WITH SR$_4$ STRAIN GAUGES

See Figure 3

	Load Lbs.	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16
		Strain Recorded in Micro Inches Per Inch					
	0	0	0	0	0	0	0
	2,000	140	141	175	131	211	120
	4,000	290	290	325	282	375	260
	6,000	434	440	475	430	531	410
	8,000	580	591	625	588	690	558
	10,000	725	740	775	730	840	700
	12,000	879	889	925	888	995	850
	14,000	1,048	1,035	1,064	1,051	1,070	1,035
	16,000	Yielding					
Return to	15,000	Opened	1,205	1,053	1,225	1,728	Opened
Return to	16,000						
Return to	0	Opened	20,315	18,563	Opened	Opened	Opened

Notes to Table 6

1. Bar Diameter=0.750 ± 0.001 inches.
2. Yielding occurred at 15,450 pounds.

TABLE 7

STRAINS MEASURED ON LOADING SECOND BAR MOUNTED WITH SR4 STRAIN GAUGES

See Figure 3

Load Lbs.	Gauge 15	Gauge 16	Gauge 17	Gauge 18	Gauge 19	Gauge 20	Ave. 17 & 18
		Strains In Micro Inches Per Inch					
50	0	0	0	0	0	0	0
1,000	60	75	80	70	75	75	75
3,000	215	220	230	220	225	220	225
5,000	375	370	380	375	380	350	378
7,000	530	515	530	520	530	505	525
9,000	685	660	680	680	690	650	680
11,000	835	800	825	830	835	790	827
13,000	1,000	950	980	975	1,000	930	977
14,000	1,065	1,030	1,050	1,050	1,065	1,030	1,050
14,750	1,080	1,115	1,120	1,100	1,120	1,090	1,110
15,250	1,095	1,150	1,160	1,140	1,160	1,120	1,150
15,750	1,095	1,200	1,200	1,155	1,225		
14,750						4,200	
16,000	1,090	1,245	1,245	1,150	1,275		
14,000	17,215	1,095	1,120	990	1,170		
15,600		1,200	1,230	1,105			
15,000					2,160		
15,250							
15,000		1,150	1,170	1,065	3,540		
15,750		1,220	1,255	1,110			
16,500			1,300				

Table 7 (Continued)

	Load Lbs.	Gauge 15	Gauge 16	Gauge 17	Gauge 18	Gauge 19	Gauge 20	Ave. 17 & 18
	16,000			1,300	1,150			
	15,000			1,300				
	15,750							
Return to	0	Opened	20,850	210	6,870	23,200	Opened	
Order of Yielding		Second	Fourth	Sixth	Fifth	Third	First	

Notes to Table 7

1. Bar Diameter 0.749 ± 0.001 inches.
2. Bar loaded up to 7,500 pounds twice and returned each time to 50 pounds before readings taken.
3. Yielding occurred at 15,750 at each gauge in turn.

(d) Machining of Specimens

Type of Specimen

The trend in the United States has been toward the increasing use of the V-notch Charpy Specimen for evaluating the relative brittleness of steels.(6) This also seems to be the case in Great Britain where in 1952 the Charpy V-notch was recommended for adoption as the test to be used as a yardstick for comparing materials and other methods of testing.(27) Tipper (15) states "the Charpy test has been accepted for the comparative study of materials."

The use of the V-notch Charpy Specimen means that it is possible to compare results with the vast amount of data accumulated by the National Bureau of Standards, Washington, D.C. where most of the welded ship casualties were investigated.(27,28)

On the basis of the trend toward increasing use of the V-notch Charpy specimen and also since the study is comparative in nature, it was decided to use this specimen for this series of tests.

Machining Work

The specimens were all machined at a commercial machine shop in strict adherence to ASTM Standards (29) for Type A of the Simple Beam Impact Specimens (V-notch).

A special milling cutter was used. The workmanship was of a high order throughout. The specimens were very uniform in dimension with practically no measurable variation between specimens. All dimensions and tolerances were in accord with the ASTM Standard.

(e) Temperature - Time History of Specimens

The material was normalized on March 5th, 1959. Straining of all bars was done at room temperature of about 70° F. from March 9th to 14th, 1959. The specimens were broken in the Charpy machine from June 24th to

29th, 1959. There were thus approximately 106 days between straining and testing. The material was at room temperature during this period.

3. Testing Apparatus

(a) Description of Charpy Machine

The specimens were all tested on the Charpy Pendulum Testing Machine shown in Figures 4 and 5. Figure 4 is a photograph of the entire machine taken from the back of the machine with the pendulum in the raised position. Figure 5 is a close-up photograph of the recording device of this machine. The pendulum raising handle and pendulum release catch is also shown in detail.

The auxillary equipment used in testing consisted of insulated containers, pliers, thermometers, dry ice and acetone.

(b) Calibration of Charpy Machine

The machine was calibrated as directed in ASTM Specification E23-56T. (29) The machine was found to be within the limits specified by ASTM except for the location of the center of percussion. ASTM specify that the center of percussion should be within ± 1% of the distance from the striking edge to the axis of rotation. This distance was found to be 1.6% too close to the axis of rotation.

An attempt was made by trial weights to correct the period of the pendulum and hence the location of the center of percussion. It was found, however, that a major modification would have had to be made on the machine. As a result it was decided to carry out these tests with the center of percussion where it was. It is felt this decision is justified since the machine is of strong construction. (29)

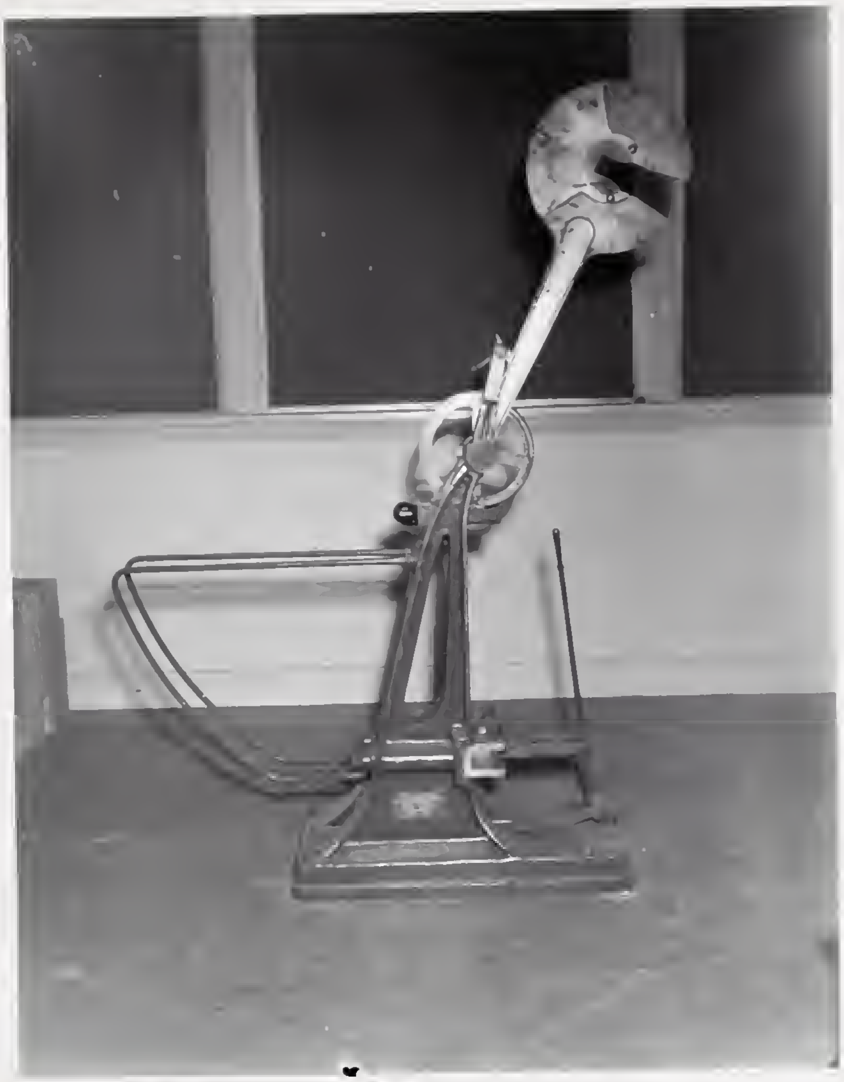


Figure 4

Charpy Pendulum Testing Machine

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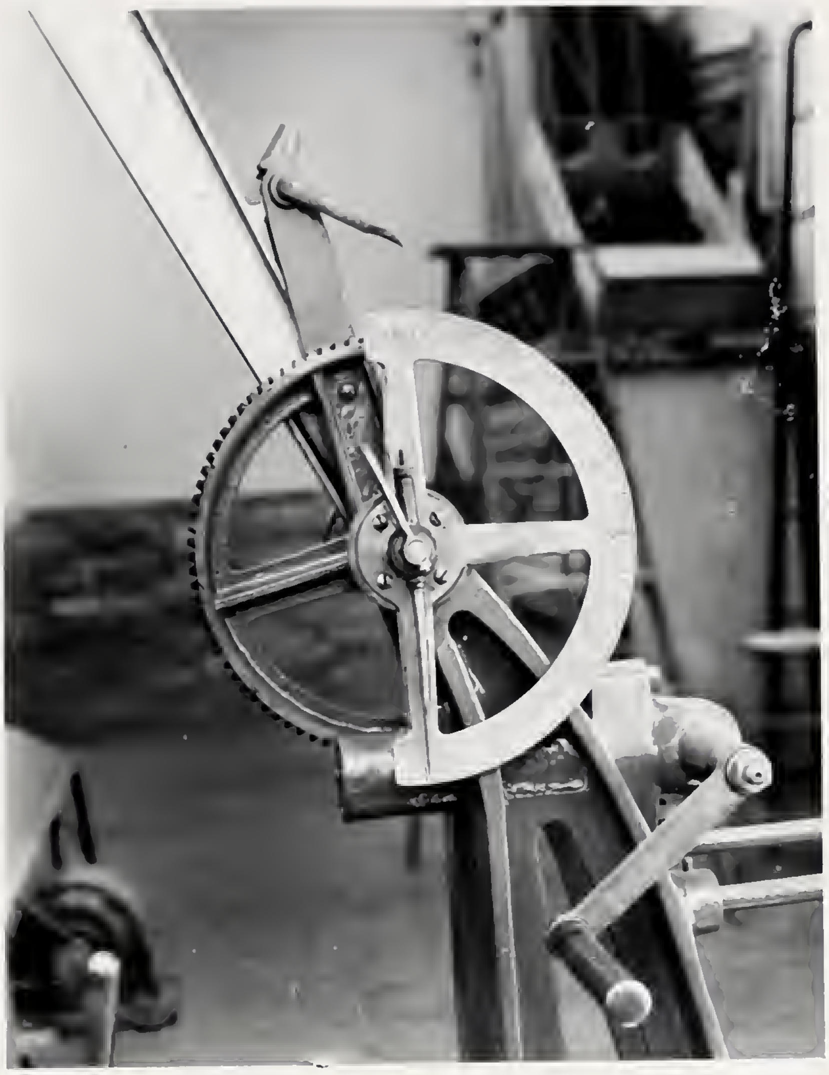


Figure 5

Charpy Pendulum Testing Machine

Close-up of Recording Device

The name plate data of this machine is as follows;

Mouton - Pendule
Systeme Charpy
No. 364 Puissance 30 KGM
4 - 1926

Pendulum: No. 364
$P = 22.665$ Kgms
$R_{CDC} = 696.5$ mm.

(c) Machine Data

The linear velocity of the pendulum was calculated as 17.4 feet per second at the center of the striking edge at the instant of striking.

The friction and windage loss was determined as 0.28% of the total energy of blow.

The energy of blow was caluclated as 217 foot pounds neglecting friction loss.

4. Testing Procedure

(a) Testing of Specimens

The actual testing of the Charpy specimens was performed in strict adherence to the procedure suggested by ASTM. (29)

A bath of acetone cooled to the appropriate temperature with chips of dry ice was found to be the most satisfactory method for tests below room temperature. For the tests above room temperature, a water bath was used.

All specimens designated for a particular temperature were placed in the bath and the temperature maintained constant within + 0° F. and - 3° F. for a full fifteen minutes. Four specimen at a time were then placed in a second bath and maintained at +0°, - 1° F. for an additional 5 minutes before testing. They were then, one at a time, quickly placed in the machine using long nose pliers.

The speed of the actual test was within the time specified by ASTM. (29)

(b) Numbering of Specimens

Each specimen was numbered individually by stamping prior to the machining of the notch. The numbering consisted of a number and a letter

followed by another number. The first number designated strain condition, the letter a particular temperature, and the last number designated the particular specimen of the two previous conditions.

A total of 234 specimens were tested. This covered five different strain conditions from normalized to 9.7% prestrain tested over a range of twelve temperatures from - 40° F. to + 100° F. In almost all cases, four specimens of each strain were tested at each temperature.

(c) Data Recorded

Six quantities were recorded for each specimen, namely, bath temperature, free swing angle, test swing angle, the lateral dimension of expansion of the back of the specimen after testing, the percentage of cleavage fracture, and whether the specimen broke or not.

The bath temperature was read to ± 1° F. immediately prior to testing the specimen.

The free swing of the pendulum was taken and read each forth test as it varied only slightly. The angles of pendulum travel were read with an estimated accuracy of ± 0.5 degrees. A photograph of the recording device showing the angle markings is shown in Figure 5. The angles are marked off in 1° intervals. In order to strictly adhere to ASTM, this scale should have been graduated in increments of 1/2°. (29)

The final dimension of the back of the specimens was measured to the closest 0.001 inch by means of a micrometer.

The percentage of cleavage fracture was determined with the aid of a magnifying glass conveniently divided off in a metric grid; the cleavage fracture area was estimated by merely counting squares. It was possible to estimate the cleavage fracture area by this method to ± 1.5% of the total area.

F. RESULTS

1. Summary of Data

Tables

The data of the 234 specimens tested are recorded in Tables 8, 9, 10, 11, and 12, which cover Strain Conditions 1, 2, 3, 4, and 5 respectively.

Plotting of Data

Three quantities were computed, namely, Energy Absorbed in foot pounds, Cleavage Fracture in per cent of area, and Lateral Expansion in per cent of width. Each of these quantities were plotted versus test temperature on individual graphs for each strain condition. Composite graphs for the five strain conditions were drawn for each of the test criterions.

In plotting the data it was attempted to choose scales which would represent the accuracy of the values measured.

Based on scale readings accurate to ± 0.5 degrees the computed value for Energy Absorbed could be in error by as much as ± 2.2 foot pounds. This error would vary slightly depending on the test angle. A scale divided to 2 foot pound increments was therefore chosen for plotting values of Energy Absorbed.

The percentage Cleavage Fracture area was determined to an estimated accuracy of ± 1.5% of total area. A scale divided to 1% increments was therefore chosen for plotting values of percentage Cleavage Fracture area.

The Lateral Expansion was determined to an estimated accuracy of ± 0.4 per cent of width. A scale divided to increments of 0.2 per cent was chosen to plot this value.

In plotting temperature values, a scale divided in one degree increments was chosen. Whereas, the bath temperature was recorded with an accuracy of ± 1 degree the actual test temperature would not be this accurate. Based on the recommendation of ASTM (29) the bath temperature was held 3 degrees below the desired test temperature for all temperatures below 10 degrees Fahrenheit. For temperatures between 39 degrees Fahrenheit and 10 degrees Fahrenheit, the bath was held 2 degrees below the test temperature. For the test at 51 degrees Fahrenheit, the bath was held 1 degree lower. In all other tests, it was assumed that the test temperature and bath temperature were the same.

Taking the above into consideration, the test temperature was probably accurate to ± 2 degrees.

Graphs

The individual graphs of Energy Absorbed versus Temperature for Strain Conditions 1, 2, 3, 4 and 5 are shown on Figures 7, 8, 9, 10 and 11 respectively. The composite graph for Energy Absorbed versus Temperature for all strain conditions is shown on Figure 12.

The individual graphs of Percentage of Cleavage Fracture versus Temperature for Strain Conditions 1, 2, 3, 4, and 5 are shown on Figures 13, 14, 15, 16, and 17 respectively. The composite graph for Percentage of Cleavage Fracture versus Temperature for all strain conditions is shown on Figure 18.

The individual graphs of Expansion versus Temperature for Strain Conditions 1, 2, 3, 4 and 5 are shown on Figures 19, 20, 21, 22, and 23 respectively. The composite graph for Expansion versus Temperature for all strain conditions is shown in Figure 24.

Description of Fractures

"There are three ways in which a fracture can be described - by its 'mode', by its 'behavior', or by its 'appearance'. (6) The 'mode' of fracture refers to the manner or form of separation, i.e. whether it follows the crystal boundaries, the slip planes of the individual crystals in the aggregate, or their cleavage planes. 'Behavior' refers to the action of the metal prior to separation, i.e. whether the fracture was preceded by extensive deformation and hence would be characterized as ductile, or whether it occurred before any significant amount of plastic flow and would be characterized as brittle. The 'appearance' refers to what one sees when observing the fracture surface."

In this series of tests only the last two factors "behavior" and "appearance" have been considered.

An attempt to evaluate behavior of the specimens was made by measuring the increase in lateral dimension after testing. It is more usual to evaluate behavior by measuring the lateral contraction at the base of the notch, (6,30) however, the former was chosen because of the inherent ease of making the measurement and because a similar procedure was followed by Hartblower (31) in V-notch Charpy Slow bend tests. This measurement has also been used by Armstrong and Warner (22) in studying the effects of composition on transition temperature.

The appearance of the specimen was evaluated by estimating the percentage area of cleavage fracture. The cleavage area had a granular or crystalline appearance and seemed to sparkle when rotated in the hand whereas the fibrous or shear fracture area had a dull gray fibrous appearance void of obvious detail. (6)

The appearance of cleavage, fibrous, and mixed fractures is shown in Figure 6. The fractures shown are representative of the various fractures obtained in these tests.

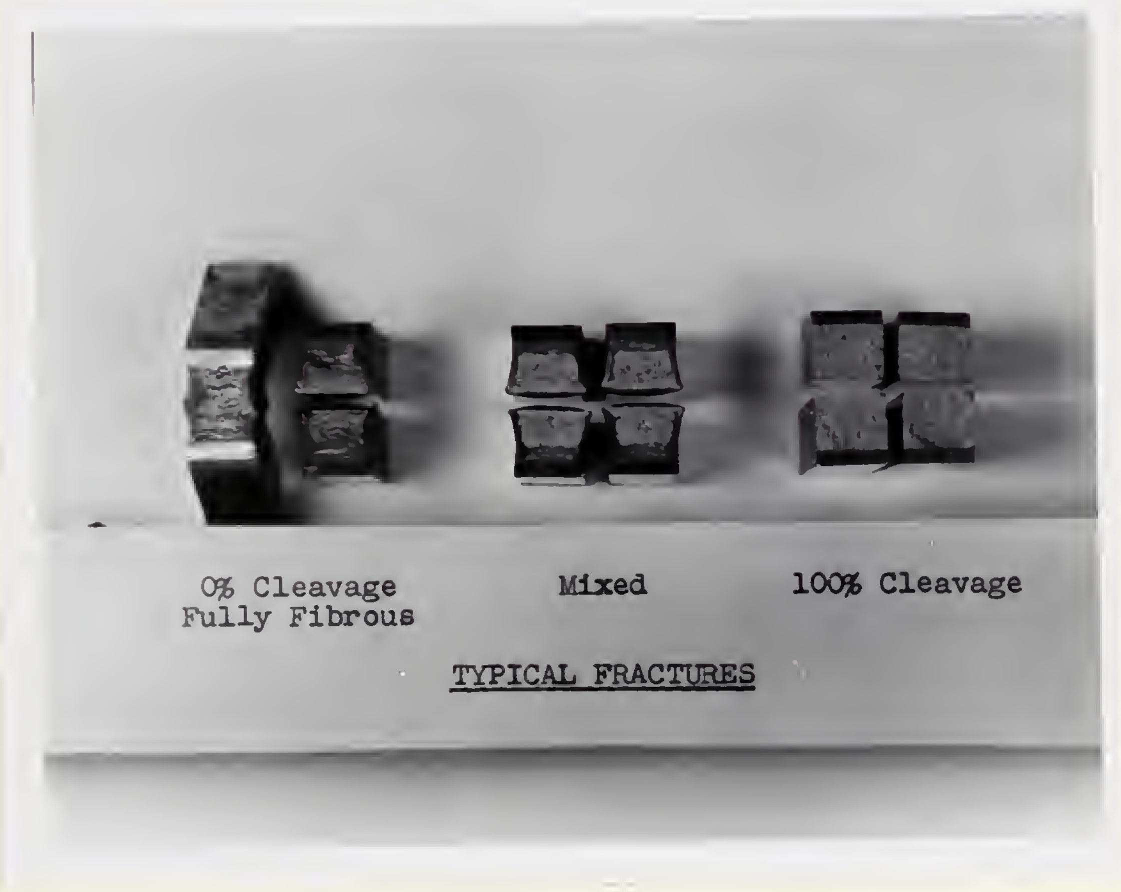


Figure 6

Appearance of Typical Fractures

2. Sample Calculation

All calculations were carried out on a slide rule except for functions of angles which were obtained from tables.

Energy Absorbed Calculation

1.	Sample Number	4KL
2.	Free Swing Angle "A"	154.4°
3.	Test Swing Angle "B"	150.0°
4.	$(A-90)^\circ$	64.4°
5.	$\sin (A-90)^\circ$	0.9018
6.	$(B-90)^\circ$	60.0°
7.	$\sin (B-90)^\circ$	0.8660
8.	$\sin (A-90) - \sin (B-90)^\circ$	0.0358
9.	Results of step 8 x 114.0 ft. lbs.	4.08 ft. lbs.

It is noted the first three steps are data recorded in the test whereas the last six steps are subsequent calculations. The above calculations were performed in tables on all the data.

TABLE 8

SUMMARY OF TEST DATA

STRAIN CONDITION 1

(Normalized)

	Temperature		Energy Absorbed		% Cleavage Fracture	Expansion of Specimen	
Specimen Number	Bath °F	Test °F	Final Angle °	Ft. Lbs.	%	%	Notes
1L1	-43	-40	146.5	7.7	85.0	3.6	OK
1L2	-43	-40	145.2	9.3	80.0	4.1	OK
1L3	-43	-40	146.1	8.2	78.8	3.3	OK
1L4	-43	-40	144.6	10.0	88.8	3.3	OK
1K1	-23	-20	143.0	11.8	73.8	4.6	OK
1K2	-23	-20	143.2	11.6	75.0	4.3	OK
1K3	-23	-20	142.2	12.8	76.3	4.6	DNB
1K4	-23	-20	142.2	12.8	76.3	5.3	OK
1H1	-13	-10	129.0	31.0	62.5	9.4	OK
1H2	-13	-10	125.0	37.4	57.5	10.9	OK
1H3	-13	-10	125.8	36.0	52.5	11.2	DNB
1H4	-13	-10	138.8	17.0	63.8	5.8	DNB
1E1	- 3	0	83.0	116.8	20.0	21.6	DNB
1E2	- 3	0	76.3	129.5	12.5	22.3	DNB
1E3	- 3	0	116.0	52.8	56.3	13.4	OK
1E4	- 3	0	131.0	28.1	60.0	8.6	DNB
1F1	+ 7	+10	102.0	79.8	41.3	18.5	OK
1F2	+ 7	+10	105.5	72.1	36.2	19.8	OK
1F3	+ 7	+10	105.5	72.1	31.2	22.3	DNB
1F4	+ 7	+10	118.6	48.1	45.0	13.4	DNB
1J1	+17	+19	103.5	76.2	35.0	17.5	DNB
1J2	+17	+19	114.8	55.0	41.3	14.2	OK
1J3	+17	+19	108.8	66.1	32.5	16.8	OK
1J4	+17	+19	67.5	146.3	0.0	22.8	DNB
1D1	+27	+29	70.0	142.0	0.0	23.6	DNB
1D2	+27	+29	93.2	96.5	26.2	21.0	DNB
1D3	+27	+29	78.0	126.5	7.5	21.8	DNB
1D4	+27	+29	69.6	142.3	0.0	21.8	DNB
1A1	+37	+39	87.8	107.0	0.0	20.0	DNB
1A2	+37	+39	94.5	93.6	26.2	20.8	DNB
1A3	+37	+39	59.5	160.1	0.0	21.3	DNB
1A4	+37	+39	60.0	159.9	0.0	22.1	DNB

Table 8 (Continued)

Specimen Number	Temperature		Energy Absorbed		% Cleavage Fracture %	Expansion of Specimen %	Notes
	Bath °F.	Test °F.	Final Angle °	Ft. Lbs.			
1G1	+50	+51	74.0	134.0	0.0	22.1	DNB
1G2	+50	+51	73.5	135.0	0.0	23.1	DNB
1G3	+50	+51	63.0	154.5	0.0	22.8	DNB
1G4	+50	+51	55.0	168.0	0.0	21.6	DNB
1M1	+63	+63	55.0	168.0	0.0	22.1	DNB
1M2	+63	+63	65.2	150.5	0.0	22.3	DNB
1M3	+81	+81	75.0	131.8	0.0	23.5	DNB
1M4	-43	-40	146.0	8.0	7.8	3.3	DNB
1C1	+80	+80	66.2	149.0	0.0	22.8	DNB
1C2	+80	+80	69.0	143.5	0.0	23.1	DNB
1C3	+80	+80	76.3	129.5	0.0	23.8	DNB
1C4	+80	+80	71.5	139.0	0.0	23.6	DNB
1B1	+100	+100	79.2	124.0	0.0	24.1	DNB
1B2	+100	+100	73.2	124.0	0.0	22.8	DNB
1B3	+100	+100	73.0	125.0	0.0	23.6	DNB
1B4	+100	+100	69.5	143.0	0.0	23.6	DNB

Notes to Tables 8, 9, 10, 11, and 12

1. Under column labeled "Notes", the specimens which broke cleanly in the machine and those which did not break cleanly are indicated by abbreviations "OK" and "DNB". "OK" indicates a clean break, "DNB" indicates specimen did not separate completely in the Charpy machine.

2. Two Temperatures are given for each specimen: The bath temperature at which the specimens were maintained prior to testing and the estimated test temperature of the specimen at the instant of striking by the pendulum.

3. Only the final angle of the pendulum is recorded for each specimen. The free swing angle of the pendulum varied between 154.0° to 154.5°, however, in practically all cases it was either 154.3°, 154.4°, or 154.5°.

TABLE 9

SUMMARY OF TEST DATA

STRAIN CONDITION 2

(Strained Just Below Yield)

Specimen Number	Temperature Bath °F	Temperature Test °F	Absorbed Final Angle °	Absorbed Ft. Lbs.	% Cleavage Fracture %	Expansion of Specimen %	Notes
2L1	-43	-40	148.1	7.2	81.2	3.0	OK
2L2	-43	-40	145.5	8.9	78.8	3.3	DNB
2L3	-43	-40	147.5	6.7	80.0	3.0	OK
2K1	-23	-20	139.0	16.8	71.3	6.3	OK
2K2	-23	-20	142.0	13.1	68.8	4.8	OK
2K3	-23	-20	139.1	16.7	73.8	6.1	DNB
2K4	-23	-20	140.1	15.4	75.0	5.6	OK
2H1	-13	-10	125.0	47.4	56.3	11.4	DNB
2H2	-13	-10	137.0	19.4	62.5	6.4	OK
2H3	-13	-10	138.5	17.3	62.5	6.4	OK
2H4	-13	-10	139.0	16.7	62.5	5.8	DNB
2E1	- 3	0	115.8	53.2	50.0	14.2	OK
2E2	- 3	0	110.0	64.0	50.0	16.0	OK
2E3	- 3	0	122.8	41.1	52.5	12.2	DNB
2E4	- 3	0	95.1	92.6	26.2	20.6	DNB
2F1	+ 7	+10	101.6	79.8	35.0	19.5	OK
2F2	+ 7	+10	112.4	59.3	46.3	15.7	OK
2F3	+ 7	+10	85.0	112.5	17.5	20.6	DNB
2F4	+ 7	+10	65.0	151.0	0.0	21.3	DNB
2J1	+17	+19	66.0	149.0	0.0	21.1	DNB
2J2	+17	+19	63.0	154.5	0.0	23.6	DNB
2J3	+17	+19	72.1	137.5	0.0	22.8	DNB
2J4	+17	+19	68.9	144.0	0.0	21.8	DNB
2D1	+27	+29	64.8	151.5	0.0	23.1	DNB
2D2	+27	+29	65.8	149.7	0.0	21.6	DNB
2D3	+27	+29	66.0	149.0	0.0	21.3	DNB
2D4	+27	+29	62.4	150.0	0.0	23.1	DNB
2A1	+37	+39	55.0	168.0	0.0	21.3	DNB
2A2	+37	+39	64.9	151.0	0.0	21.8	DNB
2A3	+37	+39	53.1	171.2	0.0	20.0	DNB
2A4	+37	+39	61.0	143.8	0.0	23.1	DNB

Table 9 (Continued)

Specimen Number	Temperature Bath °F	Temperature Test °F	Energy Absorbed Final Angle °	Energy Absorbed Ft. Lbs.	% Cleavage Fracture %	Expansion of Specimen %	Notes
2G1	+50	+51	60.0	160.0	0.0	21.6	DNB
2G2	+50	+51	66.5	148.0	0.0	23.6	DNB
2G3	+50	+51	66.0	149.0	0.0	23.4	DNB
2C1	+80	+80	72.2	137.5	0.0	24.4	DNB
2C2	+80	+80	73.6	135.0	0.0	24.6	DNB
2C3	+80	+80	70.0	142.0	0.0	23.8	DNB
2C4	+80	+80	74.5	133.0	0.0	24.1	DNB
2B1	+100	+100	68.0	145.3	0.0	22.6	DNB
2B2	+100	+100	72.1	137.8	0.0	23.8	DNB
2B3	+100	+100	69.0	143.8	0.0	24.6	DNB
2B4	+100	+100	69.5	142.9	0.0	22.3	DNB

TABLE 10

SUMMARY OF TEST DATA

STRAIN CONDITION 3

(2.5% Prestrain)

Specimen Number	Temperature		Energy Absorbed		% Cleavage Fracture %	Expansion of Specimen %	Notes
	Bath °F	Test °F	Final Angle °	Ft. Lbs.			
3L1	-43	-40	150.1	4.0	100.0	1.8	OK
3L2	-43	-40	148.0	6.3	93.7	3.0	OK
3L3	-43	-40	151.5	2.6	96.3	1.5	OK
3L4	-43	-40	150.0	4.1	100.0	1.5	OK
3K1	-23	-20	149.8	4.4	90.0	2.0	OK
3K2	-23	-20	148.8	5.4	87.5	2.5	OK
3K3	-23	-20	150.2	4.0	90.0	1.3	OK
3K4	-23	-20	149.5	4.7	85.0	1.8	OK
3H1	-13	-10	146.6	7.7	80.0	4.0	DNB
3H2	-13	-10	147.7	6.5	81.2	2.5	DNB
3H3	-13	-10	146.5	7.7	80.0	3.3	DNB
3H4	-13	-10	149.1	4.9	78.8	2.8	DNB
3E1	- 3	0	141.1	14.2	72.5	5.1	OK
3E2	- 3	0	131.8	26.9	53.8	7.9	DNB
3E3	- 3	0	146.8	7.5	78.8	3.6	DNB
3E4	- 3	0	149.0	5.2	83.7	1.8	DNB
3F1	+ 7	+10	137.0	19.5	72.5	6.4	OK
3F2	+ 7	+10	---	---	76.3	9.4	OK
3F3	+ 7	+10	131.8	26.9	67.5	8.9	DNB
3F4	+ 7	+10	134.8	22.6	67.5	7.4	DNB
3J1	+17	+19	109.8	64.0	41.2	15.9	OK
3J2	+17	+19	129.8	29.8	61.2	9.1	DNB
3J3	+17	+19	136.8	19.6	68.8	7.3	DNB
3J4	+17	+19	109.0	65.6	45.0	16.1	OK
3D1	+27	+29	108.0	67.5	36.2	16.8	DNB
3D2	+27	+29	66.0	149.0	0.0	21.3	DNB
3D3	+27	+29	103.0	76.1	31.2	19.3	OK
3D4	+27	+29	109.0	65.8	35.0	16.4	DNB
3A1	+37	+39	91.8	99.2	23.8	20.2	DNB
3A2	+37	+39	70.3	141.0	0.0	22.7	DNB
3A3	+37	+39	65.5	150.0	0.0	23.0	DNB
3A4	+37	+39	100.0	83.0	32.5	19.2	DNB

Table 10 (Continued)

Specimen Number	Temperature		Energy Absorbed		% Cleavage Fracture %	Expansion of Specimen %	Notes
	Bath °F	Test °F	Final Angle °	Ft. Lbs.			
3G1	+50	+51	62.2	155.8	0.0	22.5	OK
3G2	+50	+51	62.0	156.4	0.0	22.7	OK
3G3	+50	+51	61.0	158.0	0.0	22.5	DNB
3G4	+50	+51	83.0	159.0	0.0	21.4	DNB
3M1	+63	+63	70.0	142.0	0.0	20.4	OK
3M2	+63	+63	82.0	118.6	1.3	20.2	OK
3M3	+63	+63	58.9	161.0	0.0	18.9	DNB
3M4	+63	+63	61.1	120.1	0.0	19.9	DNB
3C1	+80	+80	75.2	131.8	0.0	22.8	DNB
3C2	+80	+80	72.0	138.0	0.0	22.3	DNB
3C3	+80	+80	77.5	127.2	0.0	23.1	DNB
3C4	+80	+80	66.5	148.2	0.0	22.1	DNB
3B1	+100	+100	75.5	131.2	0.0	22.3	DNB
3B2	+100	+100	73.8	134.9	0.0	22.3	DNB
3B3	+100	+100	79.2	124.0	0.0	23.1	DNB
3B4	+100	+100	73.6	135.0	0.0	23.3	DNB

TABLE 11

SUMMARY OF TEST DATA

STRAIN CONDITION 4

(4.9% Prestrain)

Specimen Number	Temperature Bath °F	 Test °F	Energy Absorbed Final Angle °	 Ft. Lbs.	% Cleavage Fracture %	Expansion of Specimen %	Notes
4L1	-43	-40	150.0	4.1	97.5	1.5	OK
4L2	-43	-40	151.1	3.0	97.5	1.5	OK
4L3	-43	-40	150.8	3.3	100.0	1.5	OK
4L4	-43	-40	151.0	3.1	98.8	1.8	OK
4K1	-23	-20	150.0	4.1	88.8	2.0	OK
4K2	-23	-20	150.1	4.0	88.8	1.3	OK
4K3	-23	-20	149.2	4.9	88.8	2.5	OK
4K4	-23	-20	148.2	5.9	88.8	3.0	OK
4H1	-13	-10	149.2	4.8	85.0	2.0	DNB
4H2	-13	-10	147.0	7.1	85.0	3.0	OK
4H3	-13	-10	147.1	7.0	88.8	2.8	DNB
4H4	-13	-10	150.0	4.0	83.8	2.0	DNB
4E1	- 3	0	148.3	5.9	80.0	2.5	OK
4E2	- 3	0	135.2	22.0	78.8	6.9	OK
4E3	- 3	0	146.2	8.2	82.5	3.3	DNB
4E4	- 3	0	147.5	6.8	83.8	2.8	DNB
4F1	+ 7	+10	147.0	7.3	82.5	3.3	DNB
4F2	+ 7	+10	143.5	11.2	78.8	4.1	DNB
4F3	+ 7	+10	145.6	8.9	78.8	3.6	DNB
4F4	+ 7	+10	127.0	34.2	66.3	9.6	DNB
4J1	+17	+19	126.6	34.8	58.8	9.9	OK
4J2	+17	+19	129.5	30.2	67.5	8.9	OK
4J3	+17	+19	76.5	129.1	10.0	20.6	DNB
4J4	+17	+19	119.1	47.4	48.8	11.9	OK
4D1	+27	+29	119.0	47.6	46.3	12.7	DNB
4D2	+27	+29	119.0	47.6	48.8	16.8	OK
4D3	+27	+29	74.1	134.0	0.0	20.8	DNB
4D4	+27	+29	70.0	142.0	0.0	20.6	DNB
4A1	+37	+39	103.0	77.2	31.2	17.2	DNB
4A2	+37	+39	111.5	61.0	42.5	15.2	OK
4A3	+37	+39	84.0	114.0	0.0	20.8	DNB
4A4	+37	+39	86.3	110.1	0.0	21.3	DNB

Table 11 (Continued)

Specimen Number	Temperature Bath °F	Temperature Test °F	Energy Absorbed Final Angle °	Energy Absorbed Ft. Lbs.	% Cleavage Fracture %	Expansion of Specimen %	Notes
4G1	+50	+51	61.5	157.0	0.0	19.3	DNB
4G2	+50	+51	62.0	156.5	0.0	19.8	DNB
4G3	+50	+51	59.0	161.0	0.0	19.0	DNB
4G4	+50	+51	64.2	152.0	0.0	21.8	DNB
4M1	+63	+63	62.9	154.5	0.0	23.1	DNB
4M2	+63	+63	71.1	139.7	0.0	21.6	DNB
4M3	+63	+63	72.1	137.7	0.0	22.5	OK
4M4	+63	+63	58.3	163.0	0.0	19.5	DNB
4C1	+80	+80	70.0	142.0	0.0	21.8	OK
4C2	+80	+80	76.0	130.5	0.0	21.6	OK
4C3	+80	+80	63.8	153.1	0.0	20.8	OK
4C4	+80	+80	76.0	130.5	0.0	20.0	OK
4B1	+100	+100	76.0	130.2	0.0	22.8	DNB
4B2	+100	+100	70.5	141.2	0.0	22.3	DNB
4B3	+100	+100	66.5	148.0	0.0	22.3	DNB
4B4	+100	+100	79.5	123.6	0.0	22.3	DNB

TABLE 12

SUMMARY OF TEST DATA

STRAIN CONDITION 5

(9.7% Prestrain)

	Temperature		Energy Absorbed				
Specimen Number	Bath °F	Test °F	Final Angle °	Ft. Lbs.	% Cleavage Fracture %	Expansion of Specimen %	Notes
5L1	-43	-40	151.5	2.6	97.5	1.8	OK
5L2	-43	-40	152.0	2.2	97.5	1.8	OK
5L3	-43	-40	151.0	3.1	97.5	1.8	OK
5L4	-43	-40	151.0	3.1	100.0	2.3	OK
5K1	-23	-20	154.0	0.3	90.0	1.5	OK
5K2	-23	-20	147.1	7.1	88.8	2.3	OK
5K3	-23	-20	151.1	3.1	90.0	1.0	OK
5K4	-23	-20	150.0	4.1	90.0	1.8	OK
5H1	-13	-10	150.8	3.2	88.8	1.3	OK
5H2	-13	-10	149.1	4.9	88.8	2.0	OK
5H3	-13	-10	150.0	4.0	88.8	1.8	OK
5H4	-13	-10	151.1	2.9	88.8	1.3	OK
5E1	- 3	0	149.0	5.2	83.8	2.3	OK
5E2	- 3	0	151.0	3.2	83.8	2.3	DNB
5E3	- 3	0	151.0	3.2	86.2	2.3	OK
5E4	- 3	0	150.0	4.2	86.2	1.3	OK
5F1	+ 7	+10	129.6	30.2	63.8	8.9	DNB
5F2	+ 7	+10	147.8	6.4	80.0	3.0	DNB
5F3	+ 7	+10	149.1	5.1	80.0	2.0	OK
5F4	+ 7	+10	144.6	10.0	78.7	3.3	DNB
5J1	+17	+19	77.2	128.0	0.0	21.3	DNB
5J2	+17	+19	140.5	14.8	78.8	5.1	OK
5J3	+17	+19	77.5	127.0	0.0	21.6	DNB
5J4	+17	+19	146.0	8.2	78.8	3.3	OK
5D1	+27	+29	110.0	64.0	40.0	17.3	OK
5D2	+27	+29	143.1	11.7	73.8	3.8	OK
5D3	+27	+29	126.0	35.9	60.0	10.2	OK
5D4	+27	+29	145.0	9.5	78.8	3.8	DNB
5A1	+37	+39	77.5	134.9	7.5	16.7	OK
5A2	+37	+39	115.0	54.5	43.8	14.2	OK
5A3	+37	+39	81.6	119.2	13.8	20.8	DNB
5A4	+37	+39	144.5	100.0	73.8	4.1	DNB

Table 12 (Continued)

Specimen Number	Temperature Bath °F	Temperature Test °F	Energy Absorbed Final Angle °	Energy Absorbed Ft. Lbs.	% Cleavage Fracture %	Expansion Of Specimen %	Notes
5G1	+50	+51	131.5	27.4	62.5	8.4	DNB
5G2	+50	+51	77.5	127.0	0.0	20.8	DNB
5G3	+50	+51	73.5	135.0	0.0	21.3	OK
5G4	+50	+51	74.6	133.0	0.0	21.0	OK
5M1	+63	+63	88.5	105.8	0.0	20.3	DNB
5M2	+63	+63	87.0	108.6	0.0	21.0	DNB
5M3	+80	+80	90.2	102.0	0.0	21.6	DNB
5M4	-43	-40	150.1	3.6	100.0	1.8	OK
5C1	+80	+80	77.0	128.3	0.0	21.0	DNB
5C2	+80	+80	76.0	130.5	0.0	21.3	DNB
5C3	+80	+80	73.5	135.0	0.0	21.0	DNB
5C4	+80	+80	82.0	119.0	0.0	21.3	DNB
5B1	+100	+100	72.6	137.0	0.0	20.8	DNB
5B2	+100	+100	91.4	100.0	0.0	19.8	OK
5B3	+100	+100	78.5	125.4	0.0	21.6	DNB
5B4	+100	+100	84.0	114.7	0.0	21.6	DNB

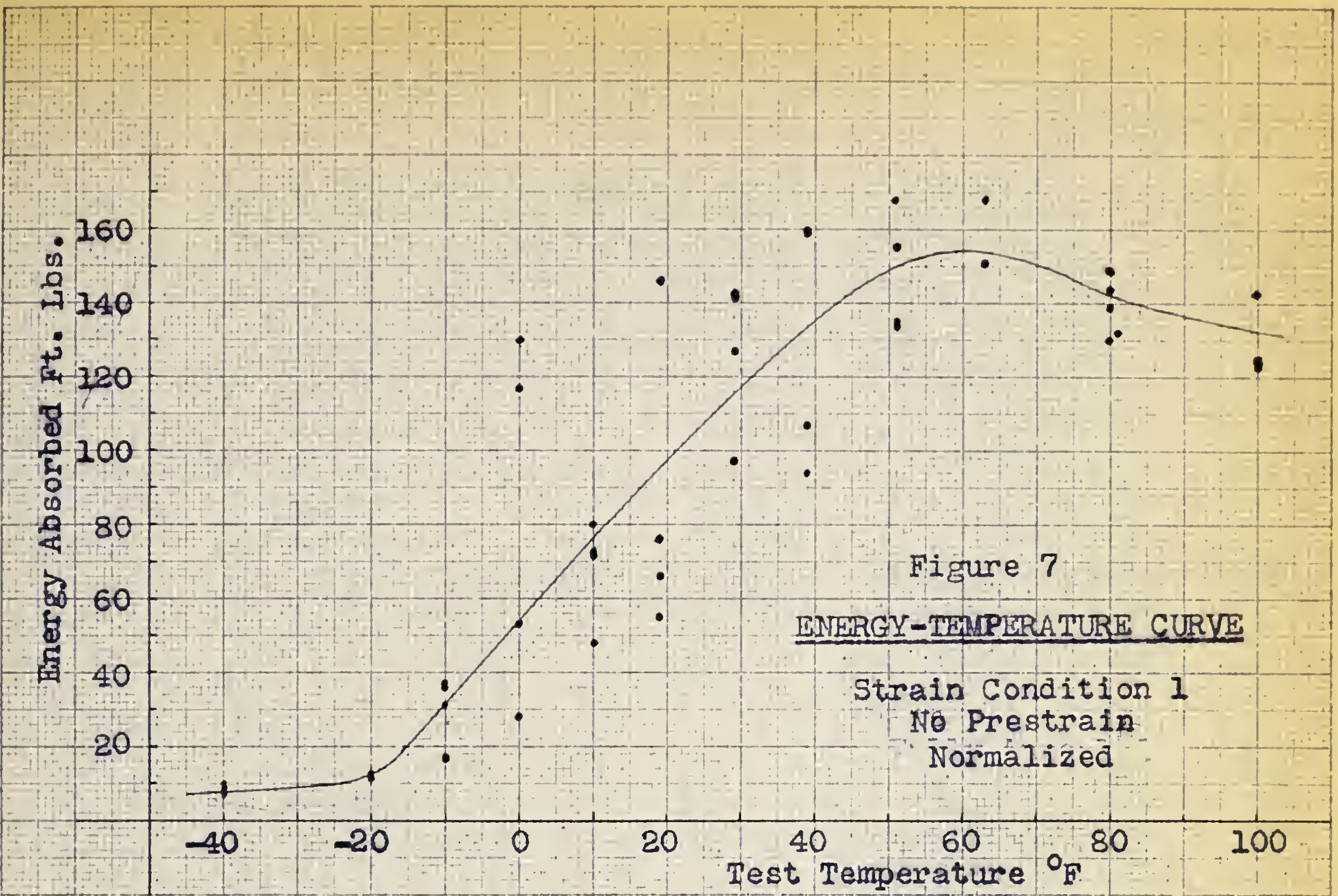


Figure 7

ENERGY-TEMPERATURE CURVE

Strain Condition 1
No Prestrain
Normalized

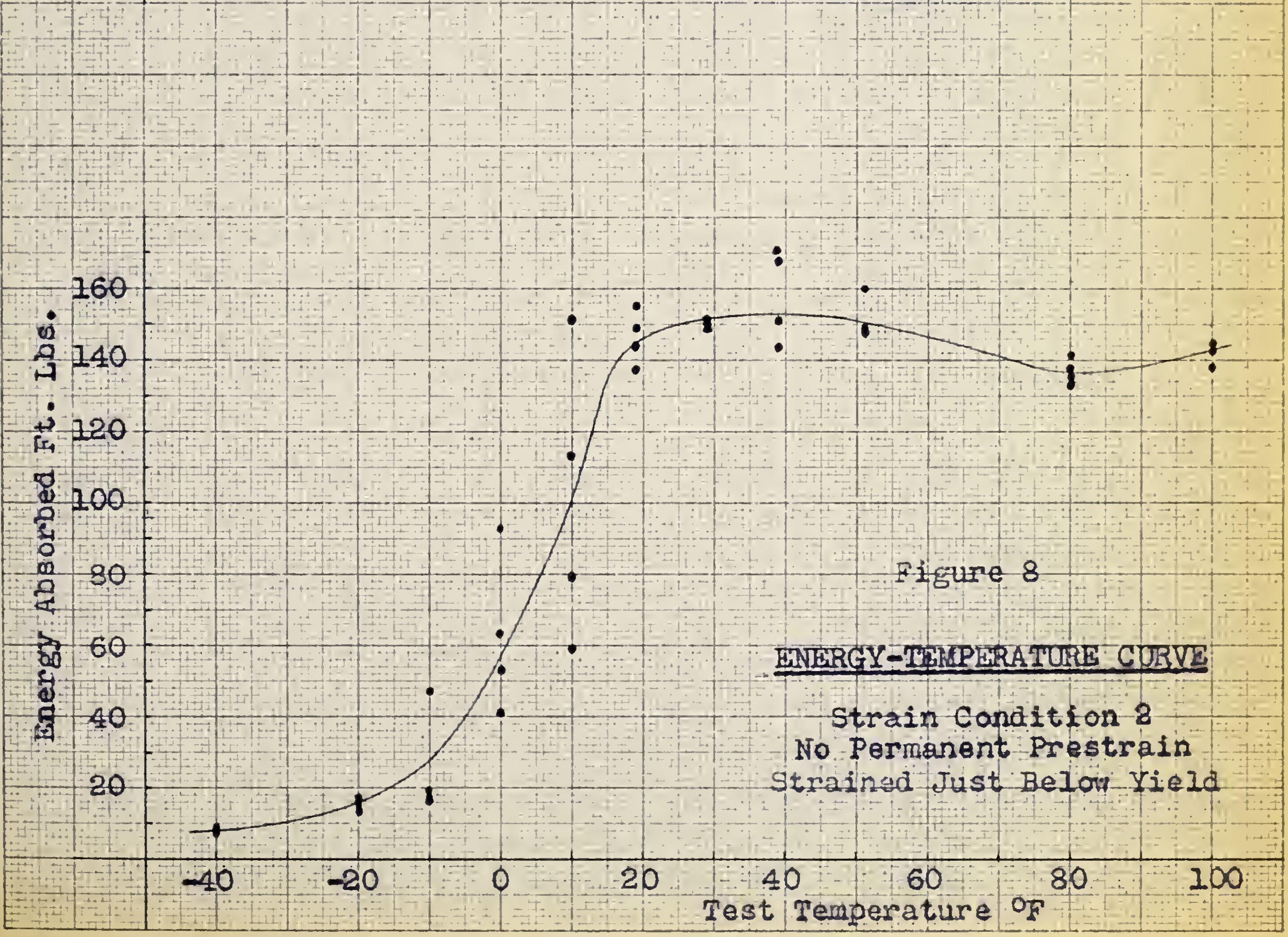


Figure 8

ENERGY-TEMPERATURE CURVE

Strain Condition 2
No Permanent Prestrain
Strained Just Below Yield

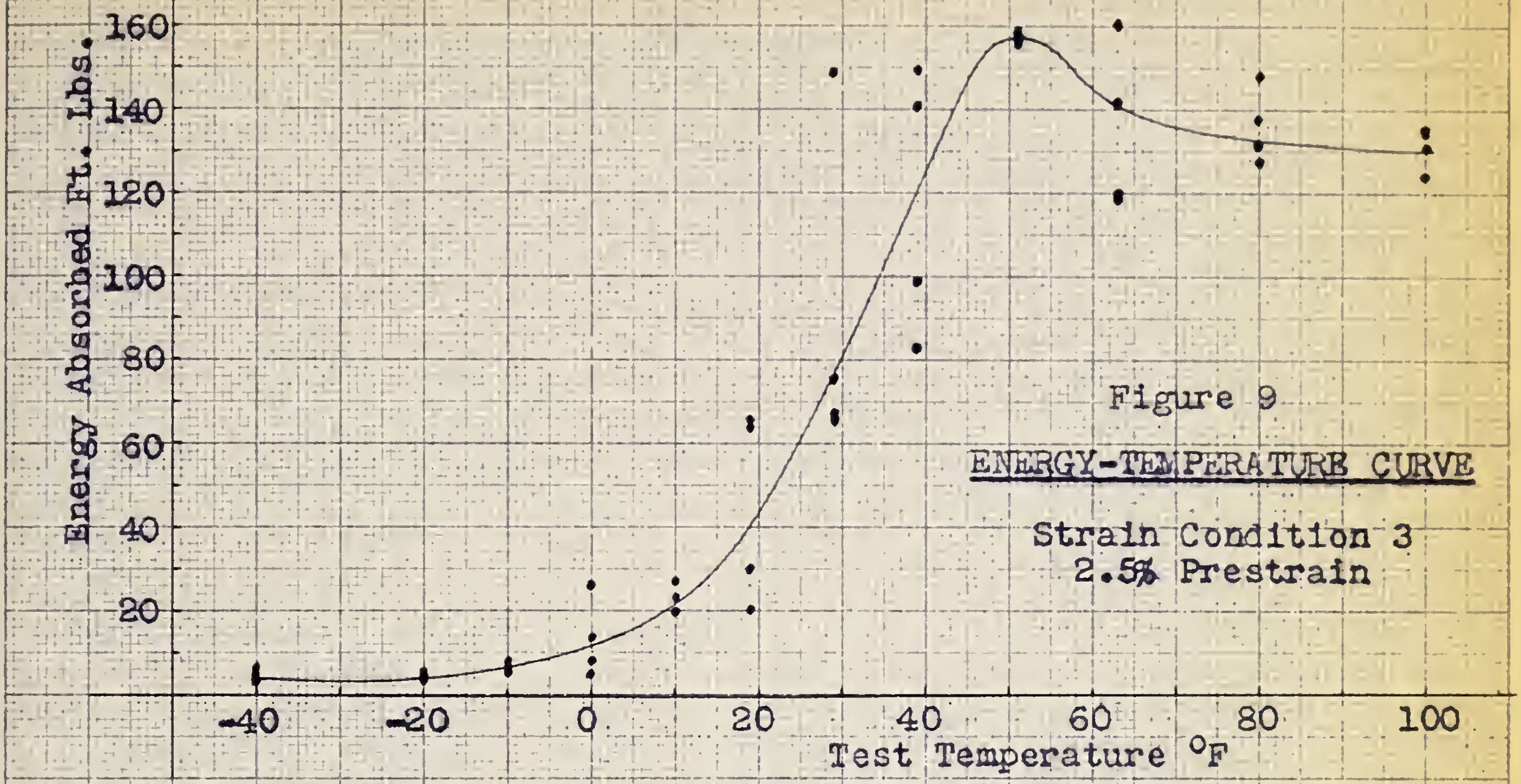


Figure 9

ENERGY-TEMPERATURE CURVE

Strain Condition 3
2.5% Prestrain

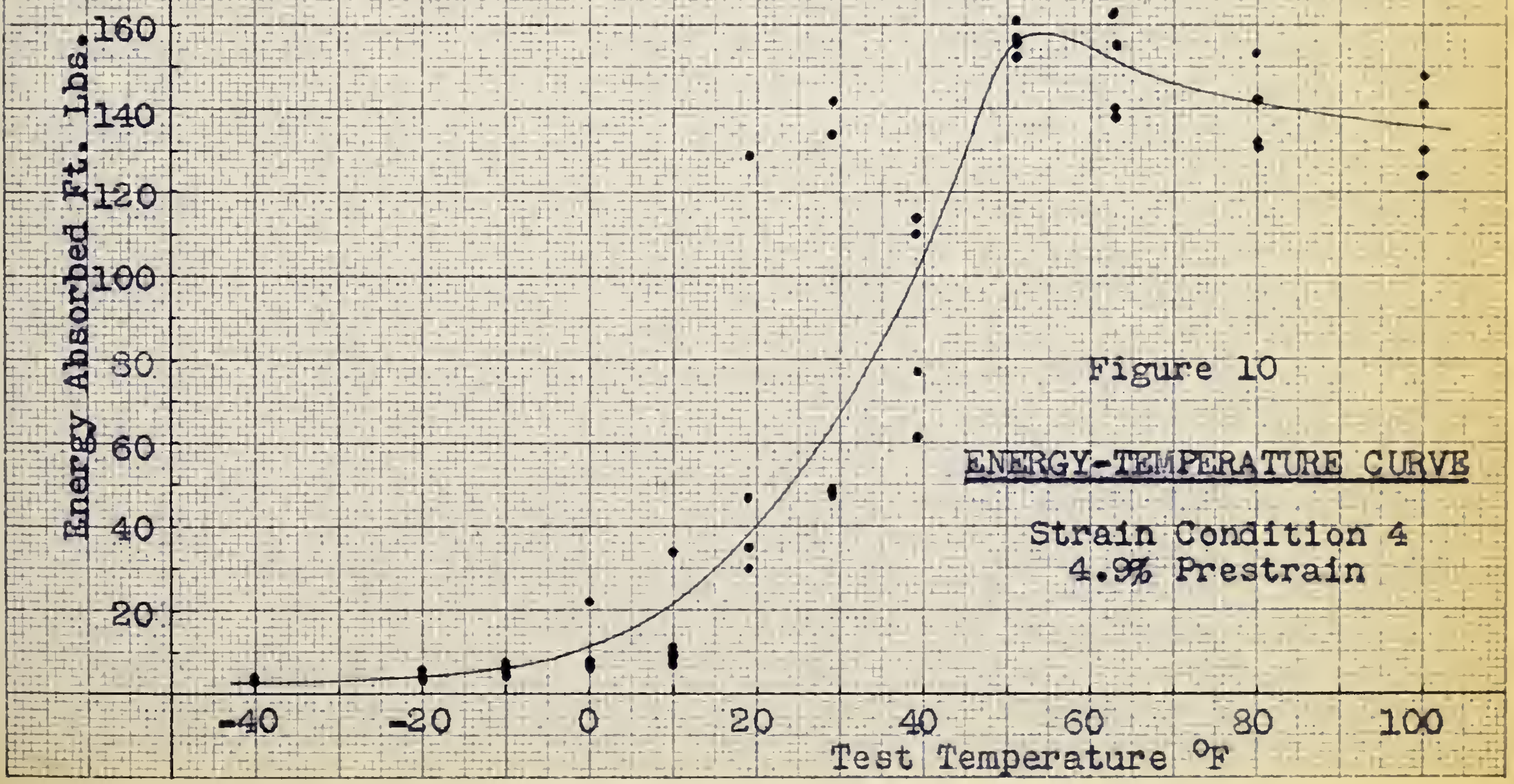


Figure 10

ENERGY-TEMPERATURE CURVE

Strain Condition 4
4.9% Prestrain

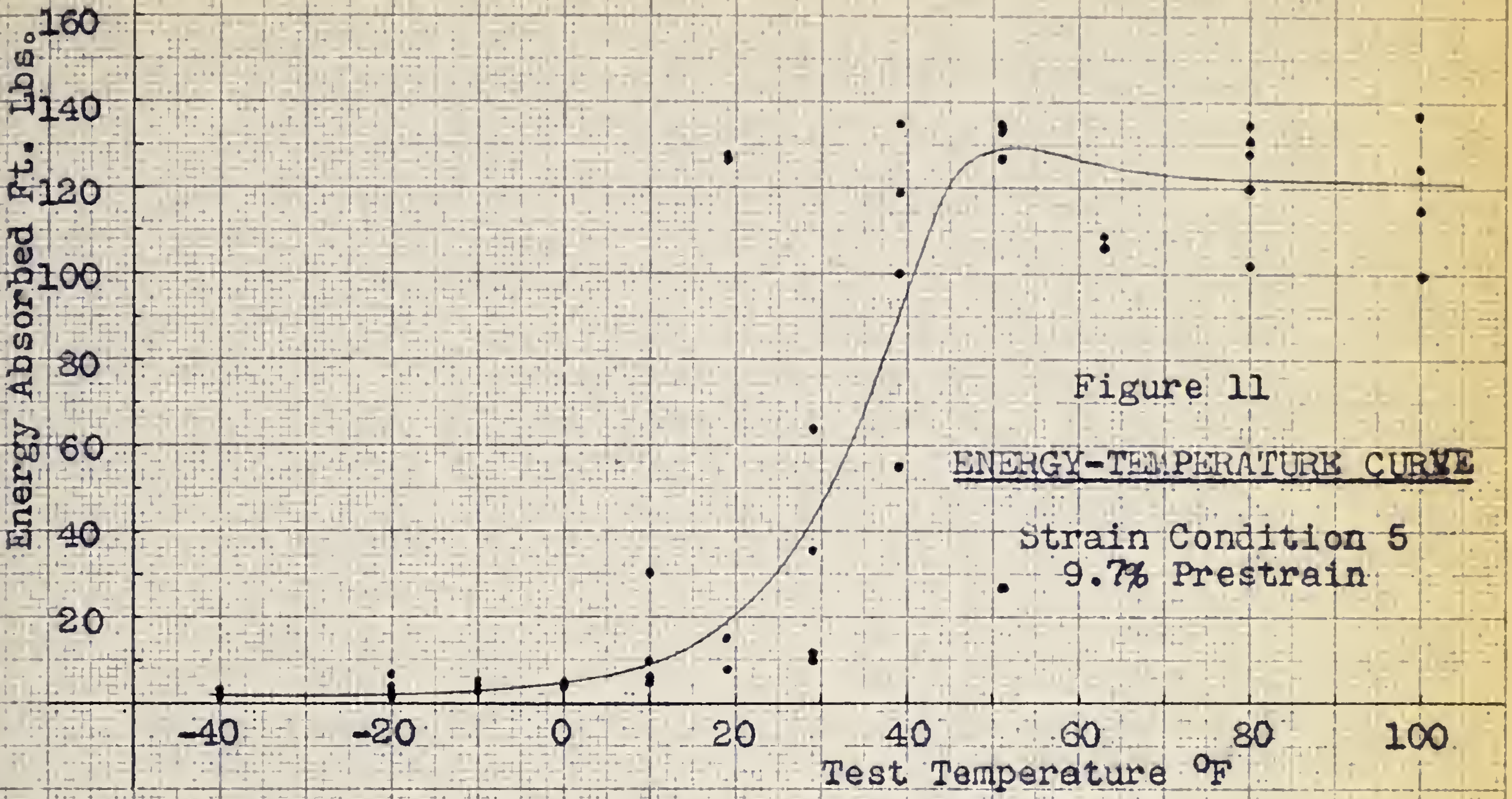


Figure 11

ENERGY-TEMPERATURE CURVE

Strain Condition 5
9.7% Prestrain

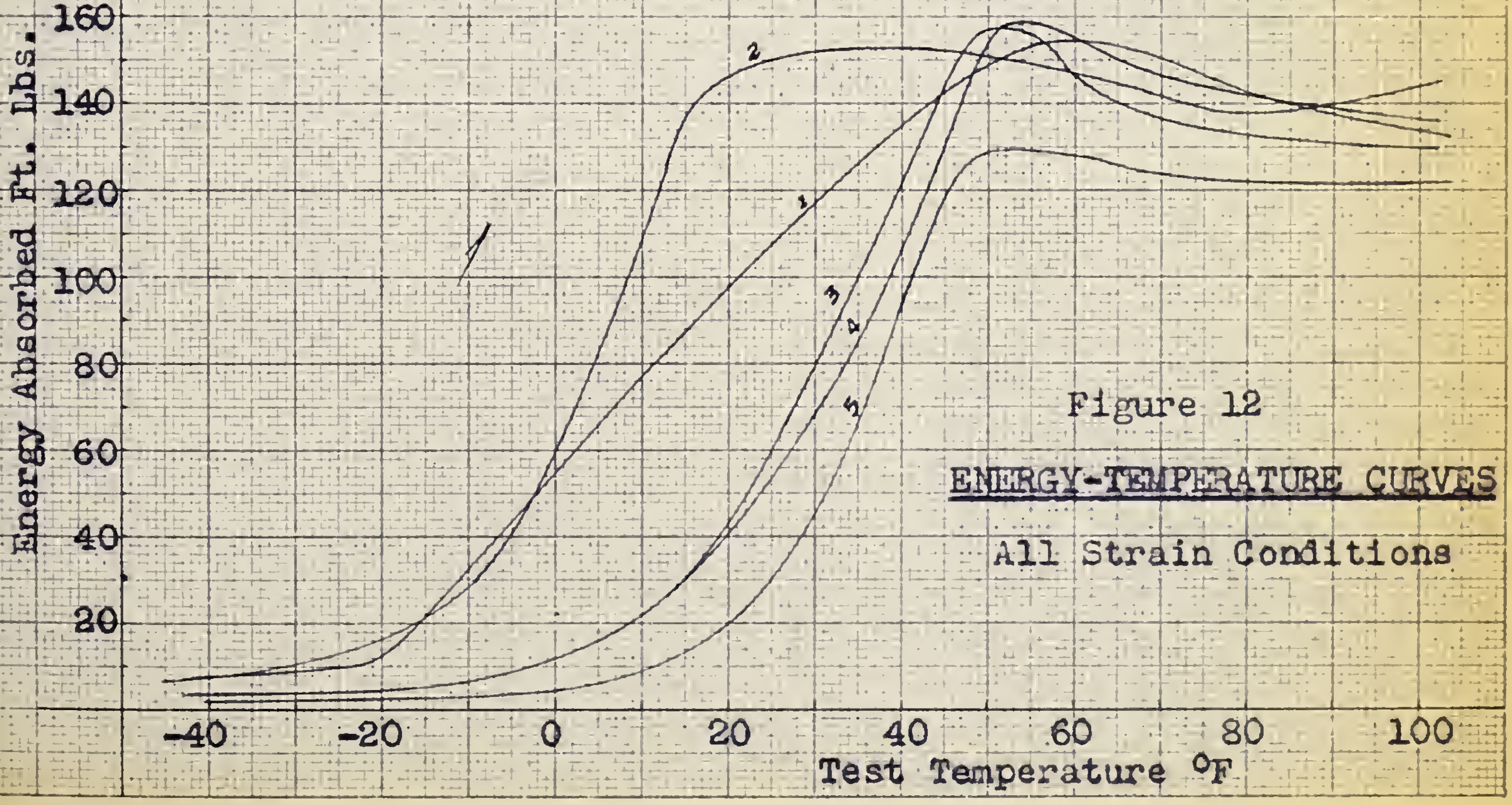


Figure 12

ENERGY-TEMPERATURE CURVES

All Strain Conditions

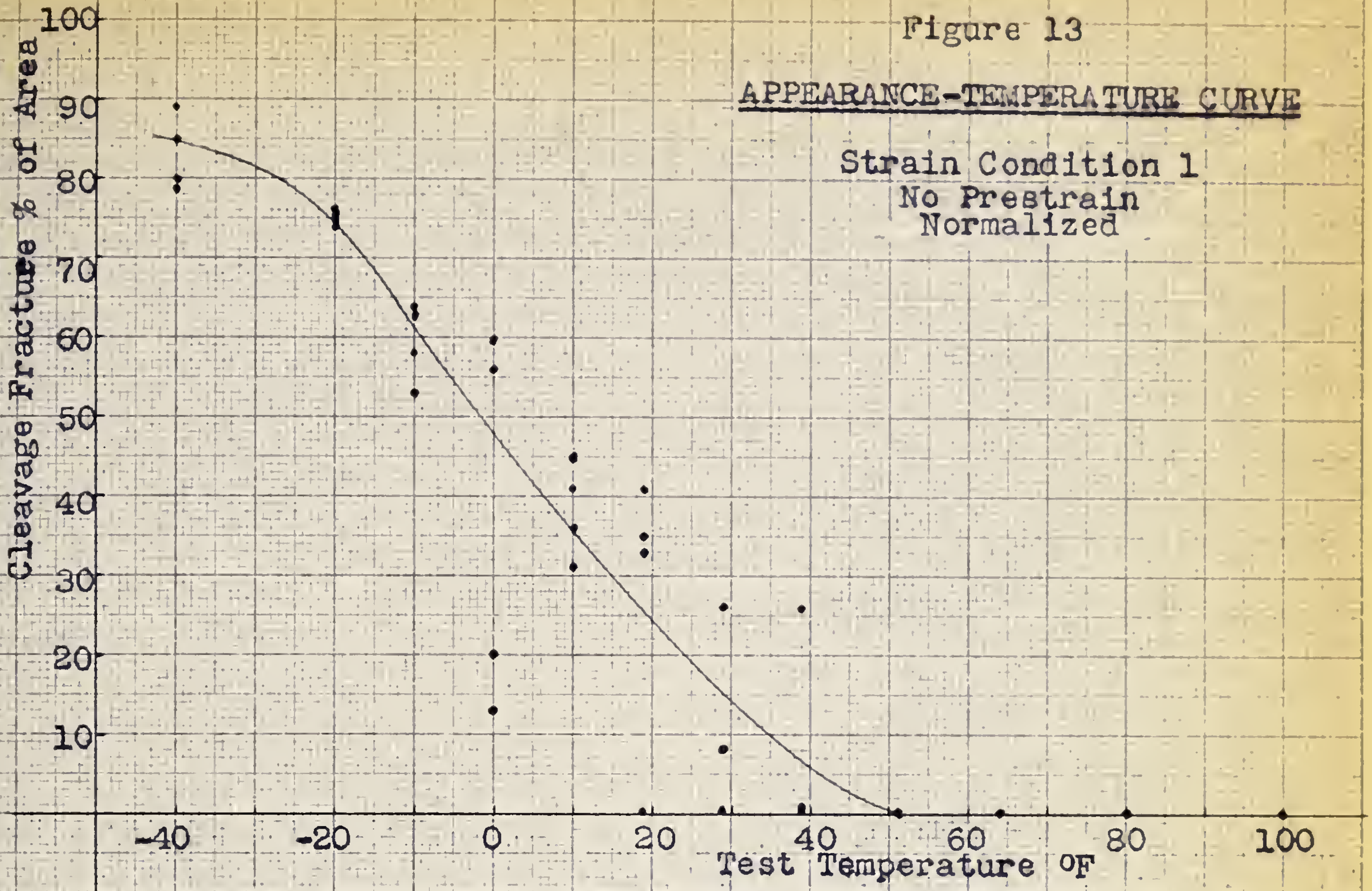


Figure 13

APPEARANCE-TEMPERATURE CURVE

Strain Condition 1
No Prestrain
Normalized

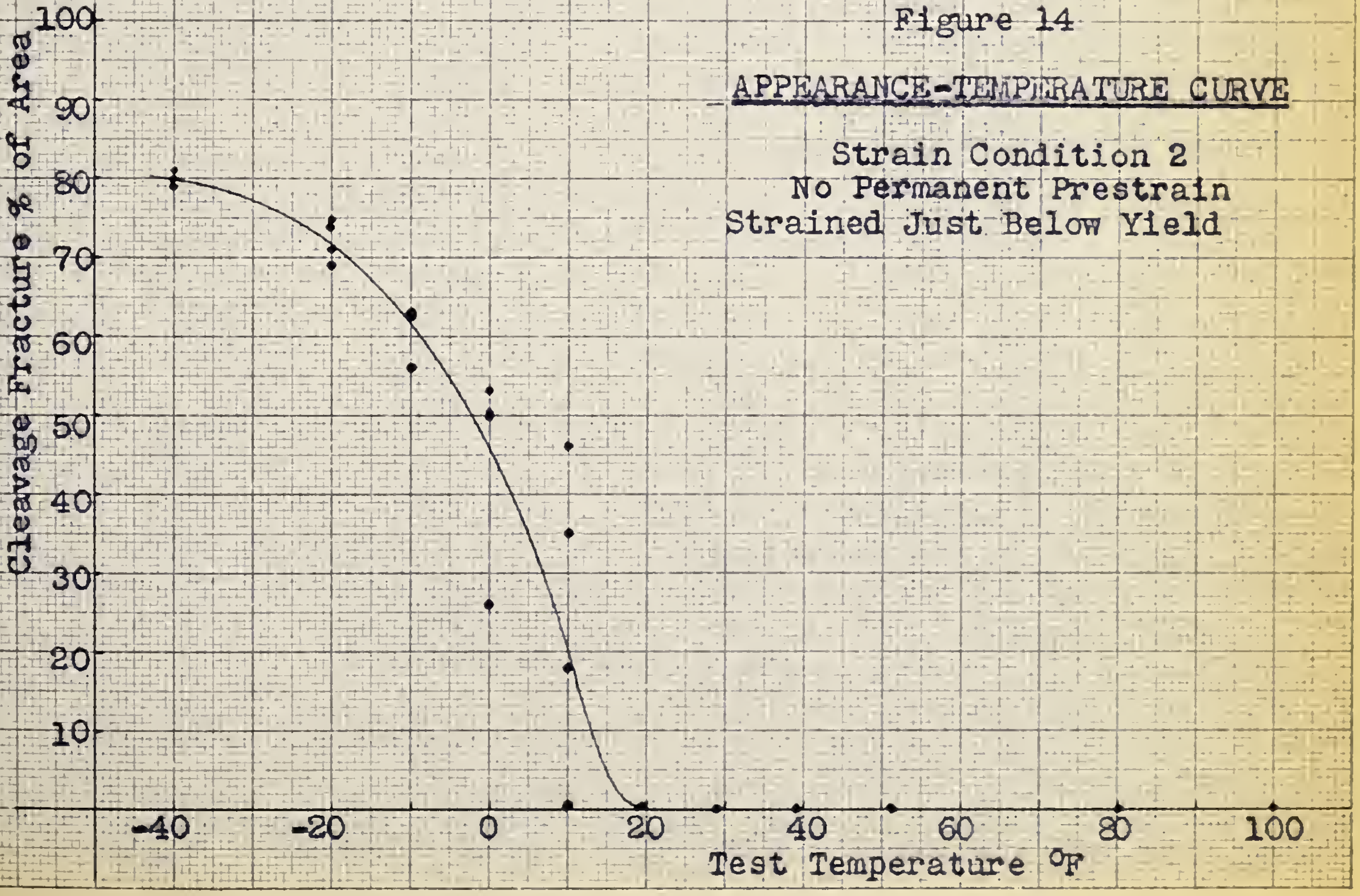


Figure 14

APPEARANCE-TEMPERATURE CURVE

Strain Condition 2
No Permanent Prestrain
Strained Just Below Yield

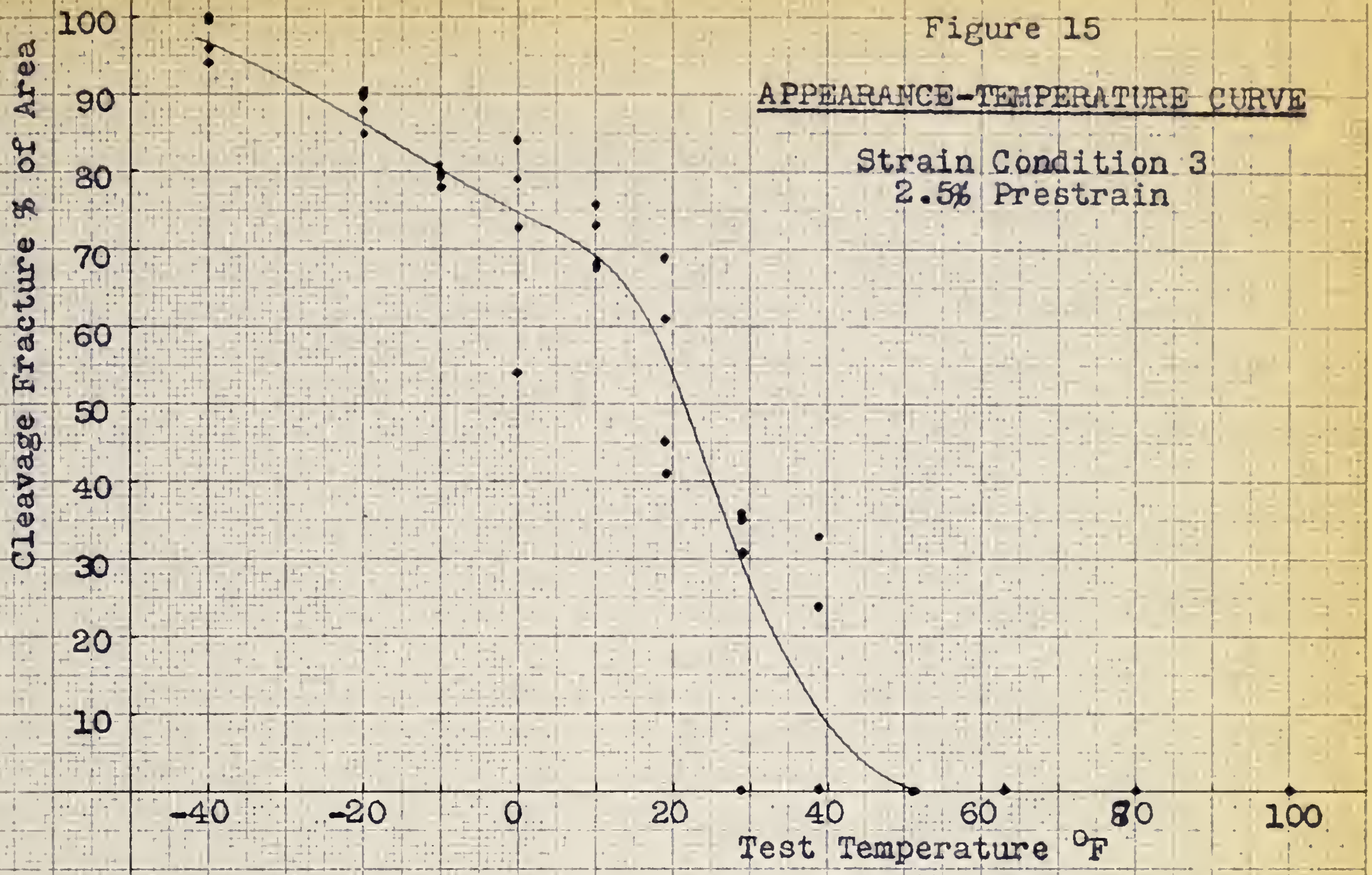


Figure 15

APPEARANCE-TEMPERATURE CURVE

Strain Condition 3
2.5% Prestrain

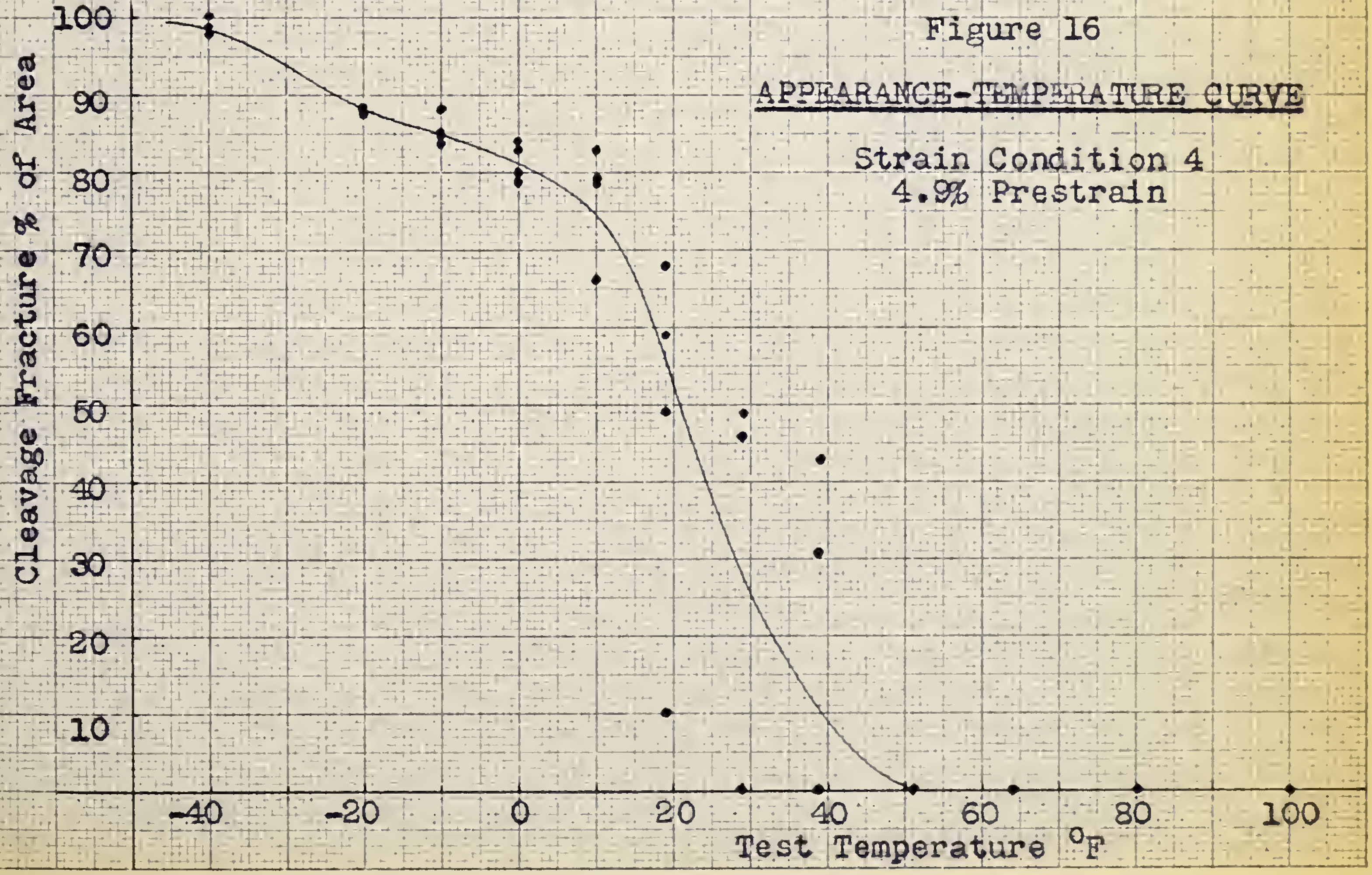


Figure 16

APPEARANCE-TEMPERATURE CURVE

Strain Condition 4
4.9% Prestrain

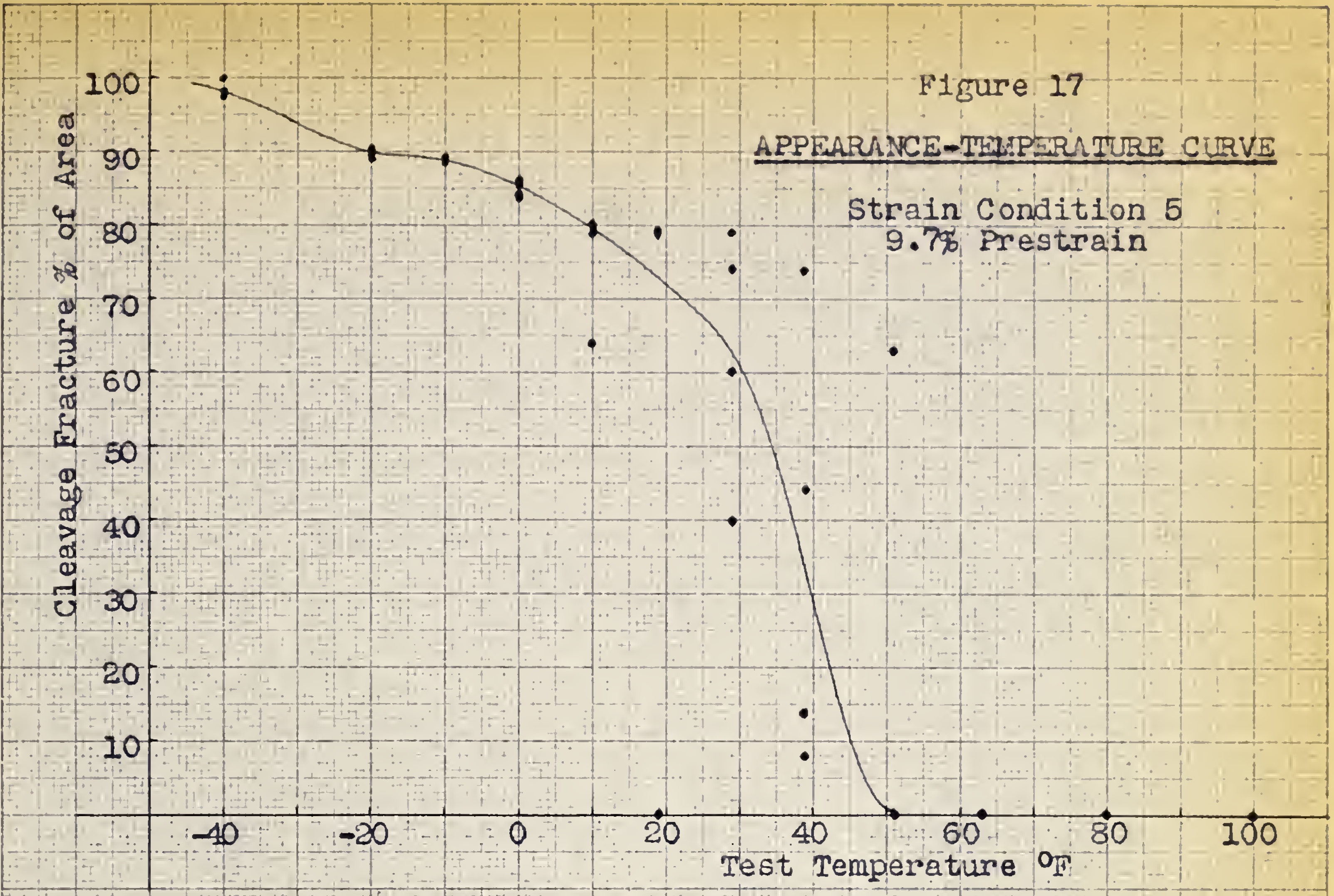


Figure 17

APPEARANCE-TEMPERATURE CURVE

Strain Condition 5
9.7% Prestrain

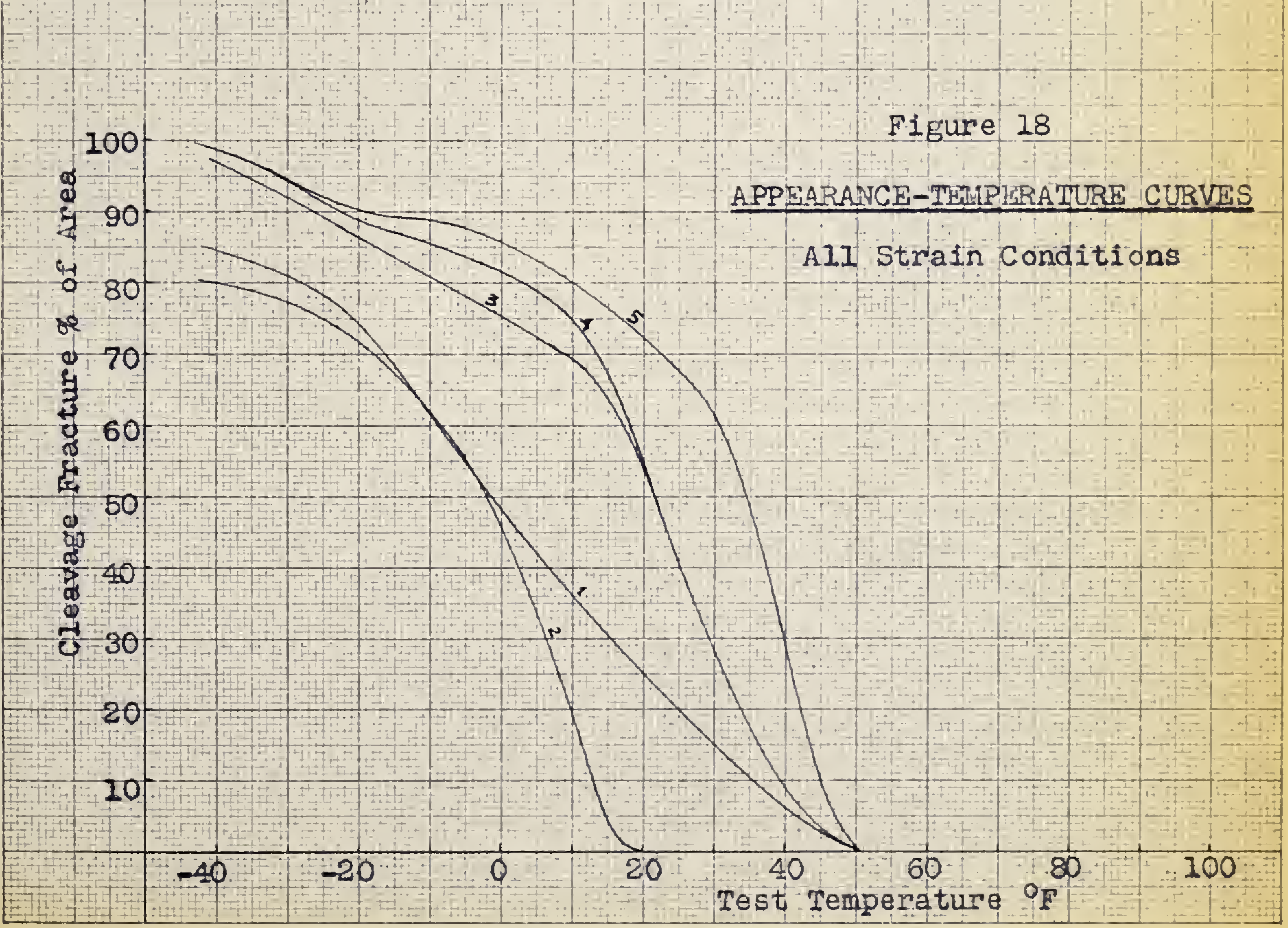


Figure 18

APPEARANCE-TEMPERATURE CURVES

All Strain Conditions

Figure 19

EXPANSION-TEMPERATURE CURVE

Strain Condition 1
No Prestrain
Normalized

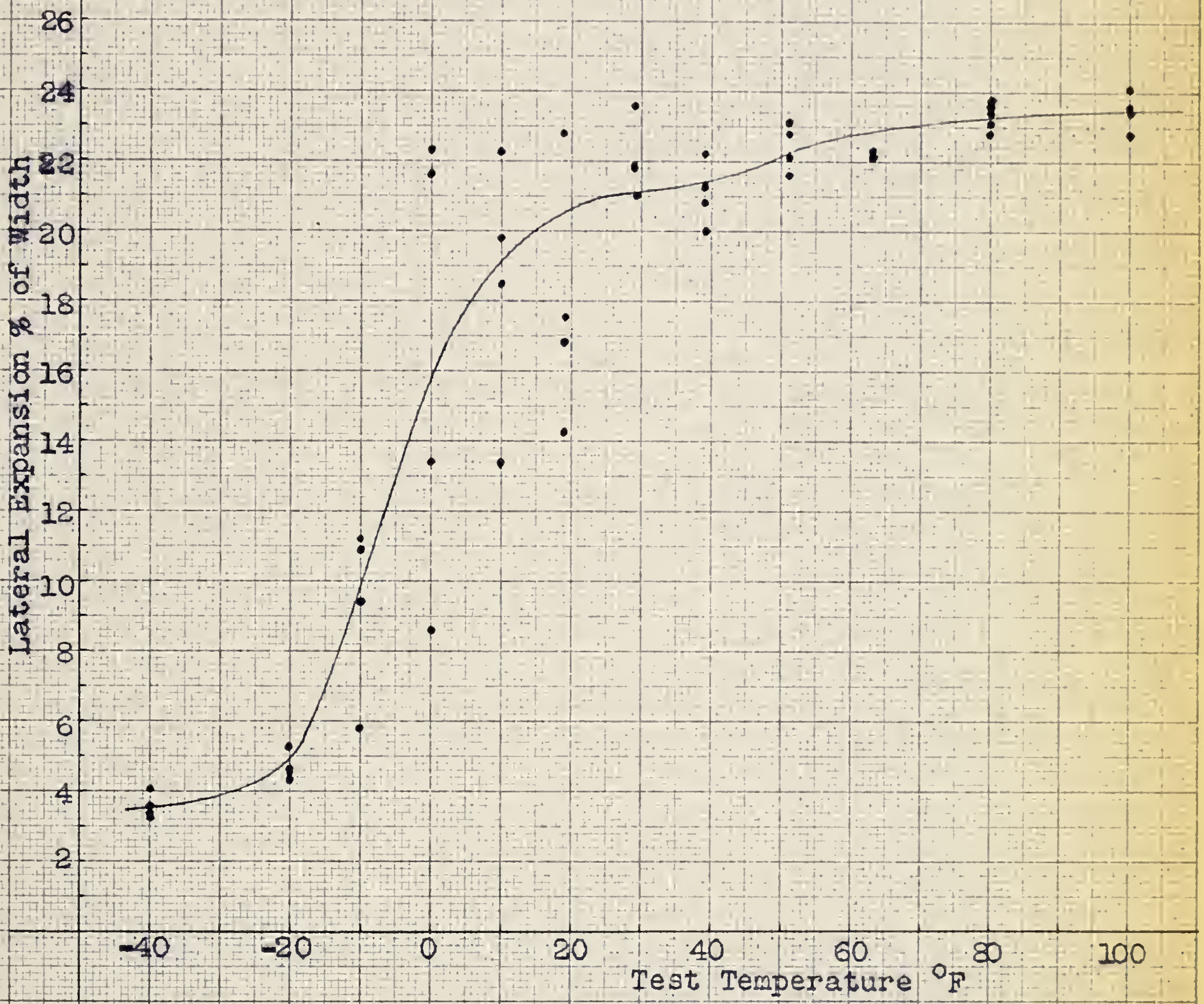


Figure 20

EXPANSION-TEMPERATURE CURVE

Strain Condition 2
No Permanent Prestrain
Strained Just Below Yield

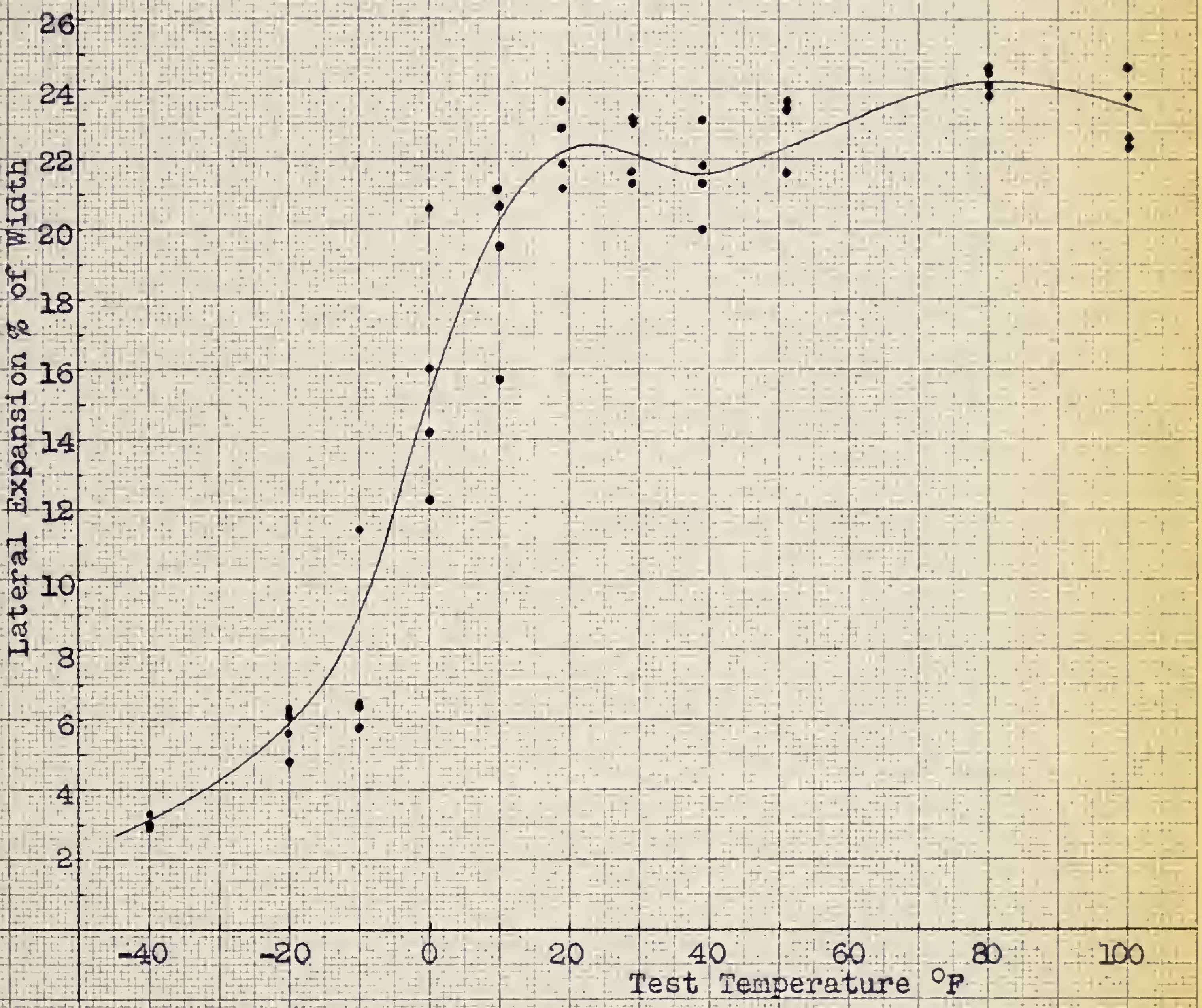


Figure 21

EXPANSION-TEMPERATURE CURVE

Strain Condition 3
2.5% Prestrain

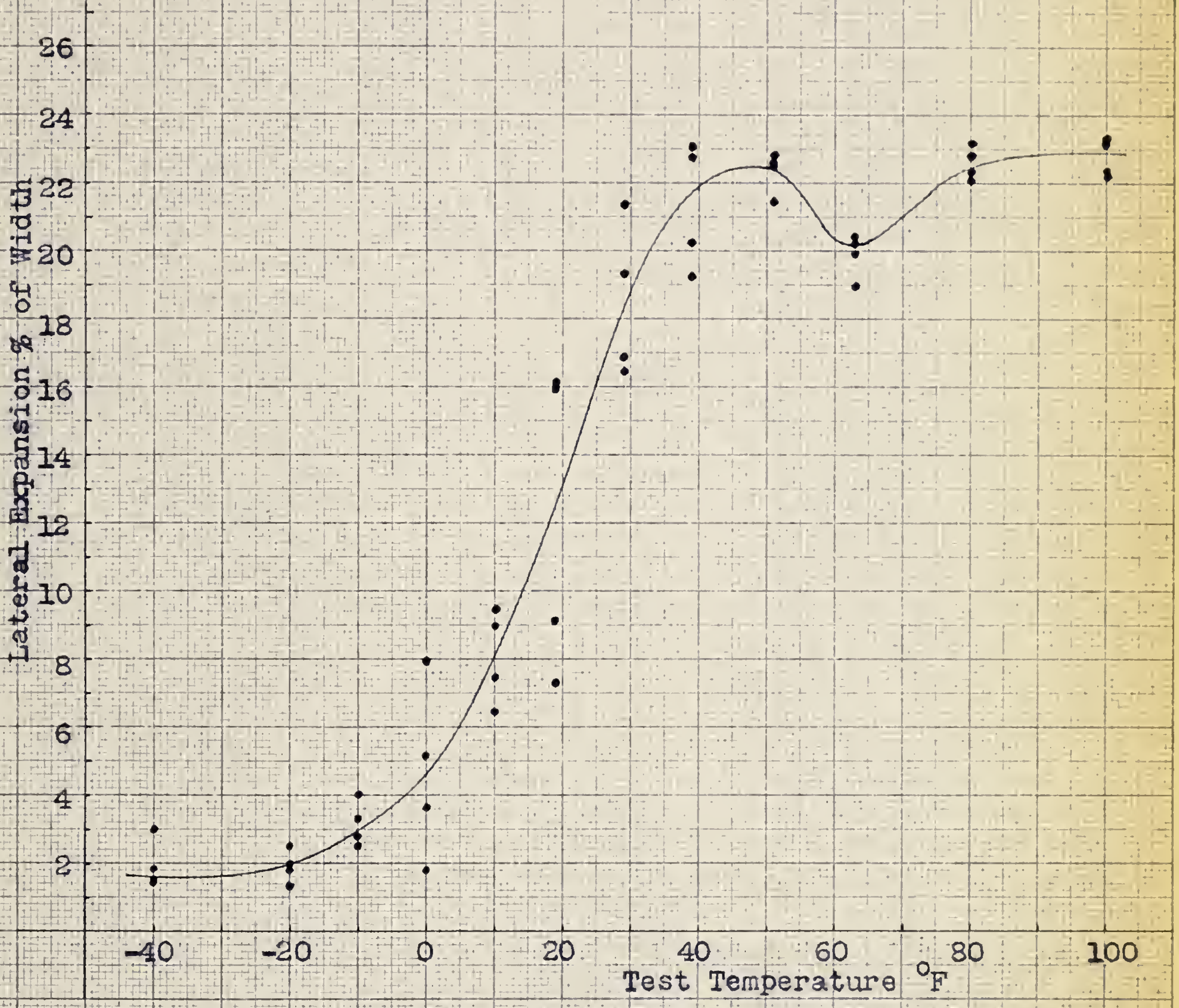


Figure 22

EXPANSION-TEMPERATURE CURVE

Strain Condition 4
4.9% Prestrain

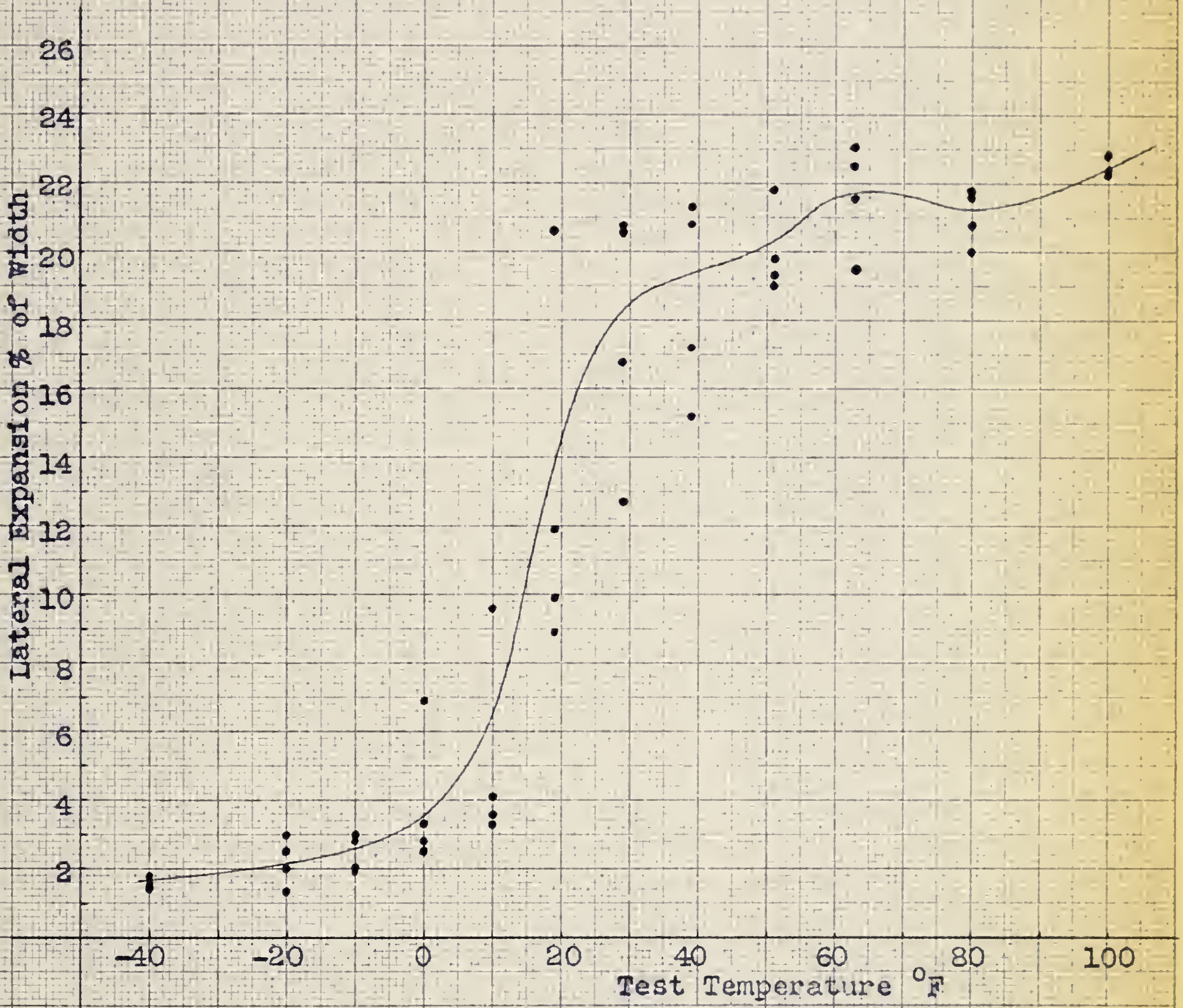


Figure 23

EXPANSION-TEMPERATURE CURVE

Strain Condition 5
9.7% Prestrain

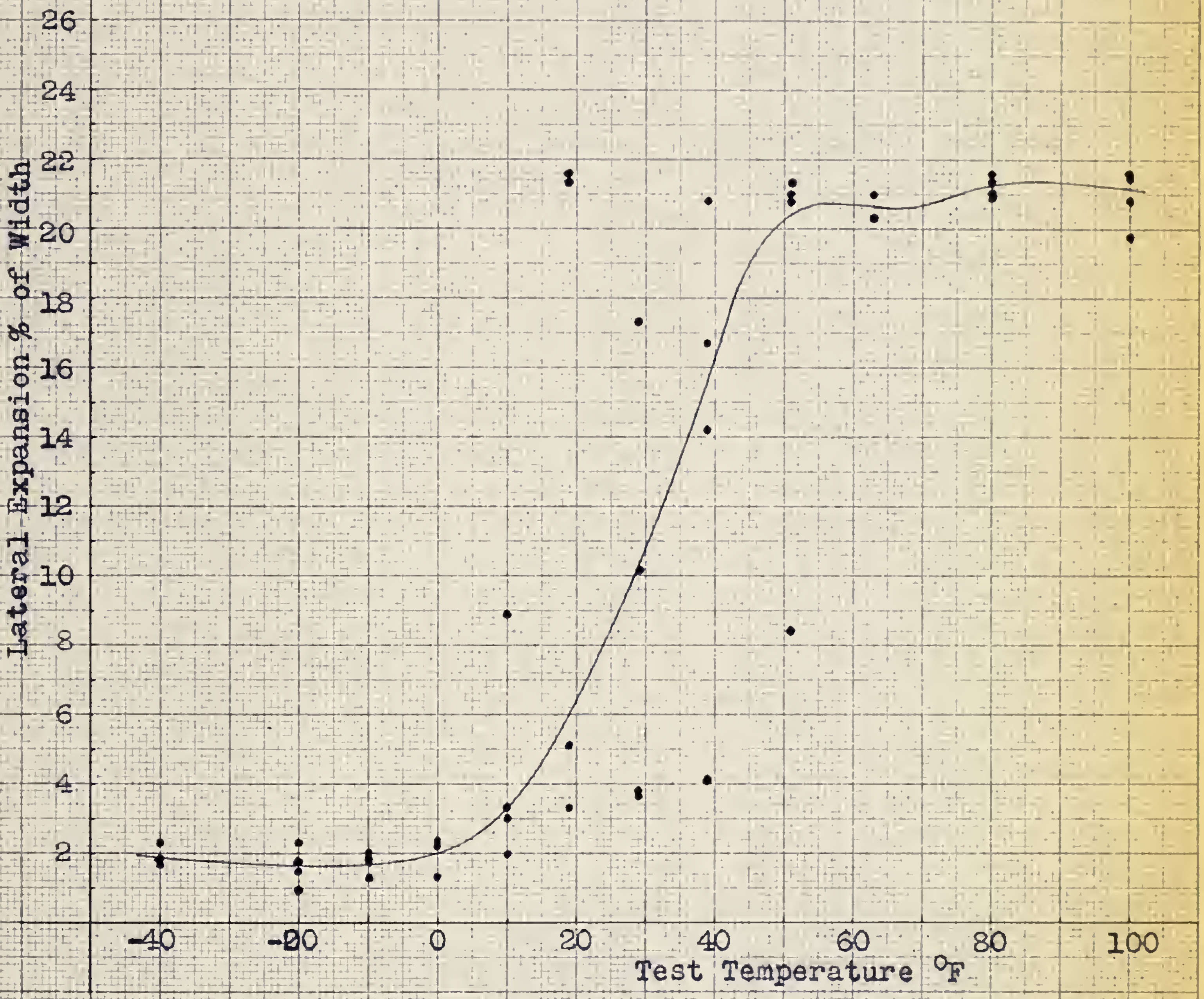
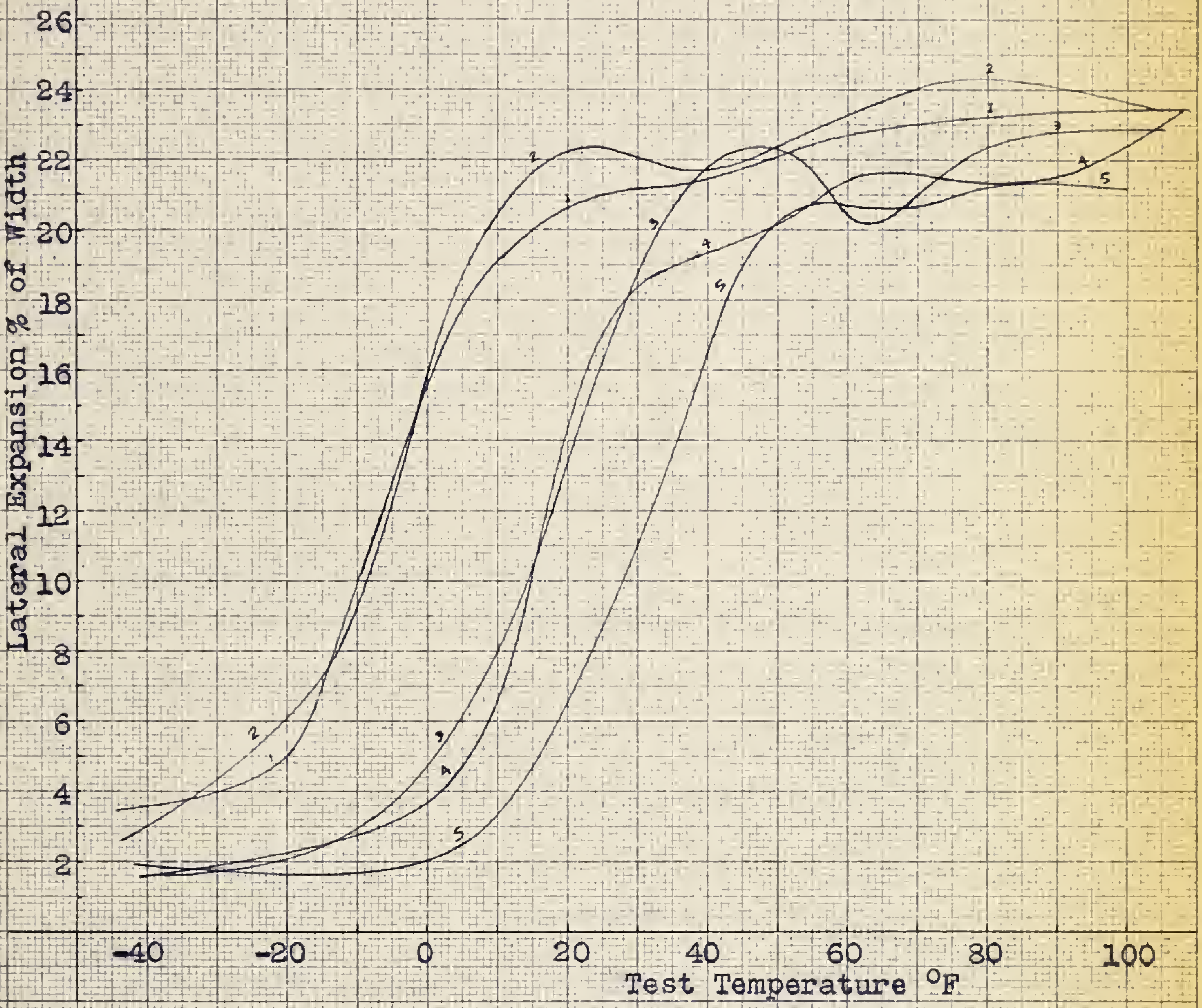


Figure 24

EXPANSION-TEMPERATURE CURVES

All Strain Conditions



G. INTERPRETATION OF RESULTS

1. Summary of Transition Temperatures

The meaning of transition temperature is dealt with elsewhere in this thesis. Some of the many definitions of transition temperature currently being used are: (29) (a) the lowest temperature that exhibits a fibrous fracture; (b) the temperature where fracture shows a 50% cleavage and 50% fibrous appearance; (c) the temperature corresponding to the energy value 50% of the difference between values obtained at 100% fibrous and 0% fibrous appearance; and (d) the temperature corresponding to a specific energy value.

A summary of the transition temperatures determined from the strained and unstrained material is listed in Table 13. Transition temperatures other than defined above are also listed and include the temperature at a specific lateral expansion at the back of the specimen and the slope of the curves in the transition range.

2. Effect of Prestrain Beyond Yield Point

There is little doubt that prestraining beyond the yield point adversely affects the transition temperature and that this effect is greater for larger amounts of prestrain. This conclusion agrees with the results of other workers summarized elsewhere in this thesis.

It is noted that prestrain from 2.5 to 4.9% raises the 15 foot pound Charpy V-notch transition temperature some 22° F. above the transition temperature of unstrained material. Prestrain of 9.7% raises this transition temperature an additional 13° F. for a total of 35° F. above that of the unstrained material.

The 50% Cleavage transition temperature was also raised 22° F. and 35° F. above the unstrained material for 2.5 to 4.9% and 9.7% prestrain

respectively. The comparable data for 8% expansion transition temperatures are 23° to 25° F. and 37° F. respectively.

To consider the effect of prestraining another way, 9.7% prestrain had the same effect on the 15 foot pound transition temperature as raising the carbon content by an estimated 0.2%. (20)

3. Effect of Prestrain Below Yield Point

Prestraining beyond the yield point adversely affects the transition temperature, however, straining just below the yield point produces a slight improvement in transition temperature.

This beneficial effect is most apparent in lowering the lowest temperature which exhibits completely fibrous fracture by 30° F. below that of unstrained material. An interesting point is that straining beyond the yield point had no effect on this criterion.

The beneficial effect of this slight prestraining is not as apparent on other definitions of transition temperatures, nevertheless, there is in most cases a slight improvement. For example, in the 50% cleavage transition, the 15 foot pound transition, and the 4% expansion transition the transition temperature is lowered 6°, 4° and 4° F. respectively. This variation could be within the margin of experimental error, however, it is consistent in all cases with the exception of the 8% expansion transition. Perhaps this improvement is due to a recovery of rheotropic brittleness. (19)

It is doubtful whether use could be made of this slight improvement in actual practice since the amount of elastic strain required would be very difficult to control.

TABLE 13

SUMMARY OF TRANSITION TEMPERATURES

Definition of Transition Temperature	Strain Condition				
	1 No Prestrain Normalized	2 Strained Just Below Yield	3 2.5% Prestrain	4 4.9% Prestrain	5 9.7% Prestrain
Lowest temperature which exhibits completely fibrous fracture	+50°F.	+20°F.	+50°F.	+50°F.	+50°F.
Temperature of 50% cleavage and 50% fibrous fracture	- 1°F.	- 2°F.	+21°F.	+21°F.	+34°F.
Temperature at which energy value halfway between max. and min. values	+12°F.	+ 6°F.	+30°F.	+32°F.	+35°F.
Temperature at:					
10 ft.lb.level	-25°F.	-32°F.	- 3°F.	- 3°F.	+12°F.
15 ft.lb.level	-18°F.	-22°F.	+ 4°F.	+ 4°F.	+17°F.
40 ft.lb.level	- 7°F.	- 5°F.	+19°F.	+20°F.	+28°F.
80 ft.lb.level	+11°F.	+ 4°F.	+30°F.	+34°F.	+38°F.
120 ft.lb.level	+32°F.	+12°F.	+40°F.	+43°F.	+46°F.
Temperature at which lateral expansion of back of specimen is:					
4%	-28°F.	-32°F.	- 3°F.	+ 2°F.	+13°F.
8%	-13°F.	-12°F.	+10°F.	+12°F.	+24°F.
Slope of Energy Temperature Curve in transition range ft.lbs./°F.	2.2	5.0	4.1	4.2	5.0
Slope of Appearance Temperature Curve in transition range % cleavage/°F.	1.2	2.8	2.8	3.1	4.0
Slope of Expansion temperature curve in transition range % Expansion/10°F.	6.0	5.8	5.8	8.0	4.8

4. Effect of Prestrain on Transition Curve Shape

No indication of the type or shape of transition curve is given in any of the usual definitions of transition temperature. This limitation may be important when comparing the relative characteristics of two steels.

Consider the case of no strain and strain just below the yield point, i.e. Strain Conditions one and two. The Energy-Temperature curves of these two Strain Conditions are compared on Figure 12. In the low energy range the two curves are very close to each other, whereas in the higher energy ranges they are apart by as much as 25° F. If the 10 or 15 foot pound level were chosen as the criterion, no recognition would be given to the better qualities of cold weather strength in Strain Condition 2. This variation in curve shape could mean the difference between satisfactory or unsatisfactory service.

Straining affected the slope of both the Energy-Temperature and Appearance-Temperature curves but did not affect the Expansion-Temperature curves. In the first two cases, all amounts of strain both above and below the yield point steepened the curves in the transition range by approximately the same amount. Once the transition had started, it occurred more rapidly for strained bars than for unstrained bars.

All improvements in properties of the material strained just below the yield (Condition 2) are a result of the increased slope of the curve in the transition range. More straining shifted the curve to higher temperatures without further increase in slope. The slight amount of straining reduced the temperature at which the transition began but left unchanged the final temperature of the end of the transition. These observations may be explained to a degree by the work of Ripling (19)

on Rheotropic Brittleness where it was found that ductility (and presumably the toughness) deficiency at Subtransition temperatures can be cured, partially at least, by cold working at a supertransition temperature before testing it at the subtransition temperature. Straining apparently does cause this recovery of Rheotropic Brittleness but the material still exhibits a transition and this transition is more sudden because of the recovery.

Straining has the opposite effect on the slope of the transition range to that of increasing the carbon content. The addition of carbon tends to flatten the curve. (6,22)

5. Scatter of Data

Most of the data plotted in figures 7 to 24 show considerable scatter, particularily in the transition range itself. The data for tests below the transition range show very little variation with the points in many cases falling one on the other. This is not true, however, for data from tests above the transition range. This latter variation is probably a result of the large number of test specimens not completely breaking at the higher temperatures.

A total of 234 Charpy specimens were broken in this series of tests. Of these, 143 or 61% failed to break apart completely during the tests. Apparently the V-notch was not severe enough for this particular material. Hoyt (32) comments on this condition, "Perhaps the worst feature of practice in this field is that of testing V-notch Charpy specimens on the Charpy machine and reporting extra high impact values of about 80 foot pounds or more even well above 100 foot pounds. In these instances the test specimen has not broken (too shallow a notch) but has been violently driven through the split anvil by the pendulum meanwhile absorbing a large

and unknown amount of energy. Obviously this situation results in absurd or fictitious values. Although the test data are unreliable in such cases, it is known at least, that the metal has responded in a tough manner with that particular notch."

In this series of tests values of energy absorbed were as high as 170 foot pounds. In the work of others (17,20) found in the available literature, values as high as 115 and 130 foot pounds for the V-notch Charpy test were noted.

The scatter within the transition zone can be accounted for in part by some of the specimens not breaking, however, this alone does not seem to be a full explanation for the wide band of values. A study of the curves shown in Figures 7 to 11 would indicate there is an envelope in the transition range where part of the data are near the top of the envelope and part are near the bottom. This envelope is similar to the usual data obtained in the Keyhole Charpy test where in the transition range there are usually either high values or low values with very few intermediate values. (6,17) This condition is not usual for V-notch Charpy data. (6)

This envelope is due to a type of instability. It is not known whether a particular specimen will exhibit predominantly tough or predominantly brittle behavior. A striking comparison can be made with other instability phenomena where there is a transition from one mode of behavior to another. Two good examples are fluid flow in round pipes and column behavior. If Reynold's number is plotted versus friction factor in fluid flow, at a certain range of Reynold's number the type flow changes from laminar to turbulent flow. (33) The same situation is found in the change from long column to short column behavior when critical stress is plotted versus the L/r ratio. (36)

6. Statistical Analysis of Data

Rinebolt and Harris (20) studied the scatter found in V-notch Charpy data. Specimens were prepared from small carefully controlled heats of one composition. After testing, the results were analysed statistically to determine what range of experimental scatter could be expected to occur on closely controlled testing. It is claimed that the results are applicable to investigations of commercial steels provided segregation, variation in grain size, directionality, and related factors are not variable enough to increase scatter.

The data, based on 15 heats and 20 specimens from each heat, produced the results shown in Table 14.

Table 14

Results of Rinebolt & Harris Analysis

Transition Temperature Definition	Standard Deviation	Number of Specimens
15 foot pound	8.2° F.	5
Average Energy	6.7	20
50% Cleavage	14.0	5
First sign of Cleavage	20.4	5

It is further stated, "The scatter found for a particular definition of transition temperature can also be expressed as a standard deviation. This quantity is used in analysing the effects of a variable such as composition on two materials which differ by a controlled amount of variable. If a difference in transition temperature results from the change it is necessary to take account of the scatter before it is certain that the difference is significant. It can be shown that the difference must exceed 2.83 times the standard deviation for the transition temperature selected if the difference is to be significant with a probability of 95%."

Assuming that the results of Rinebolt and Harris can be applied to the data of this work, (and it is not implied that this assumption is necessarily valid) the difference required for significance for the four definitions of transition temperature would be as listed in Table 15.

Table 15

Rinebolt & Harris Data As Applied To These Tests

Transition Temperature Definition	Number of Specimens	Standard Deviation	Difference for Significance
15 ft. lb.	12	5.3° F.	15.0° F.
Average Energy	48	4.3	12.2
50% Cleavage	12	9.0	25.5
First Sign of Cleavage	12	13.2	37.4

Using the difference for significance to check the data in Table 13, the following conclusions may be drawn:

1. There is no significant difference in the 15 foot pound transition temperatures or Average Energy transition temperature of either Strain Conditions 1 and 2, or Strain Conditions 3, 4 and 5, but that there is significant difference between the two groups.
2. There is no significant difference in the 50% Cleavage transition temperature between any two adjacent strain conditions but that there is significant difference between no prestrain and 9.7% prestrain.
3. There is no significant difference between temperatures at which cleavage fracture was first noted.

These conclusions appear very reasonable when the curves on Figures 12 and 18 are studied. Indeed, it is possible to surmise the same deductions without using the results of Rinebolt and Harris.

The importance of the deductions of Rinebolt and Harris, however, should not be overlooked. By establishing the standard deviation of different definitions of transition temperatures, it is possible to evaluate comparison tests using a limited amount of data. The standard deviation indicates the variation which can be expected if a particular transition temperature was determined on the same material a number of times. For example, if the 15 foot pound transition temperature were to be determined on the material of any one strain condition again, there would be about one change in twenty of the two results differing by more than ± 10.6° F. or twice the standard deviation. (34)

7. Correlation of Transition Temperatures

There is not sufficient data on any one strain condition to justify any further statistical analysis of the variation between individual specimens; however, the different definitions of transition temperature can be compared.

Plots to show the degree of correlation between definitions of transition temperature are shown on Figures 25, 26 and 27. The data are too few to rely on for conclusive evidence although there appears to be a linear relationship between the 50% Cleavage transition temperature, the low energy transition temperature, and the low expansion transition temperature.

Good correlation was found between the 50% Cleavage transition and the 15 foot pound transition. This finding is not in agreement with the work of others since straining did not affect the Ductility transition more than the Fracture transition, particularily at lower strain levels. (6,17)

The correlation of other definitions of transition temperature was not too good.

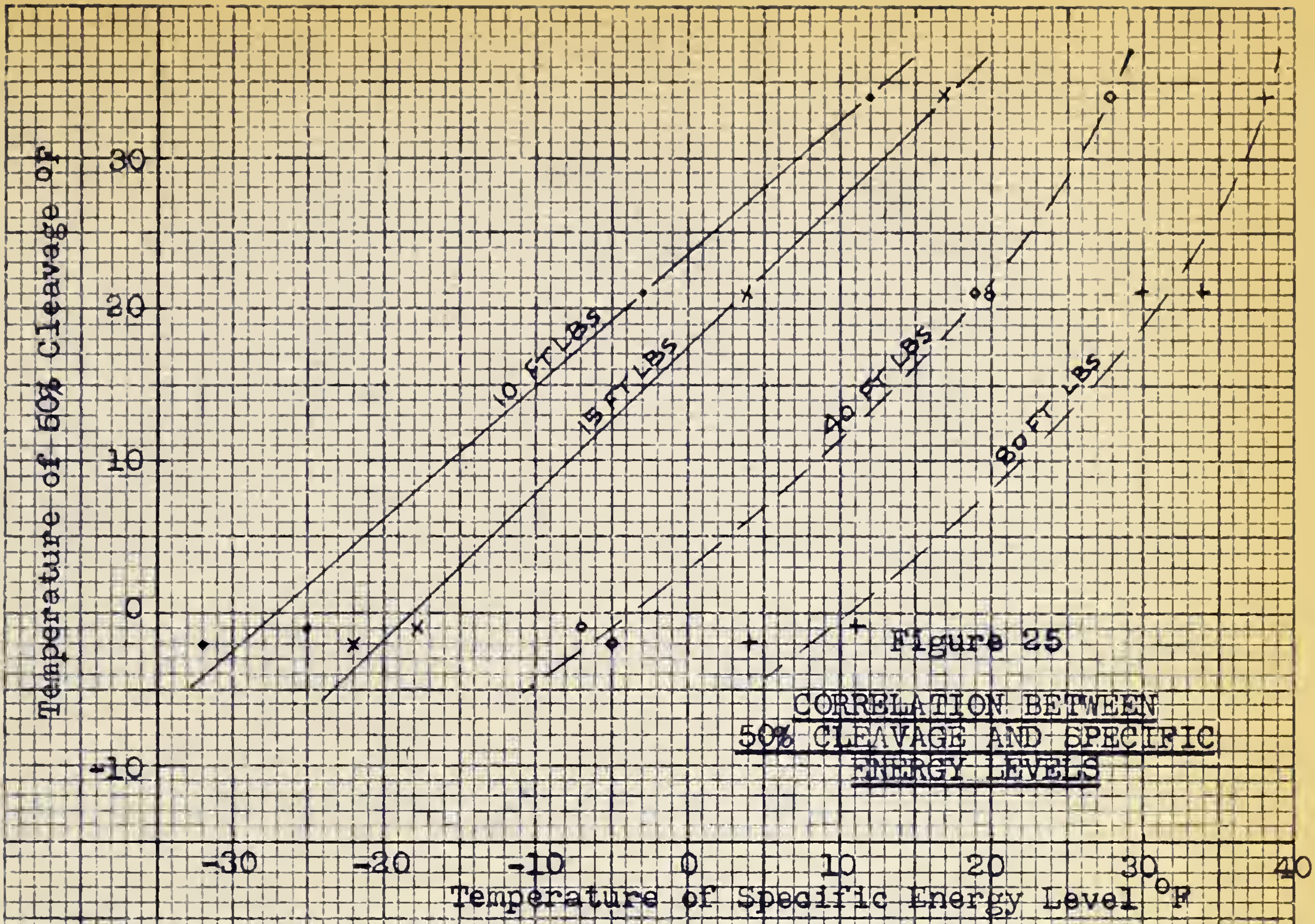


Figure 25

CORRELATION BETWEEN 50% CLEAVAGE AND SPECIFIC ENERGY LEVELS

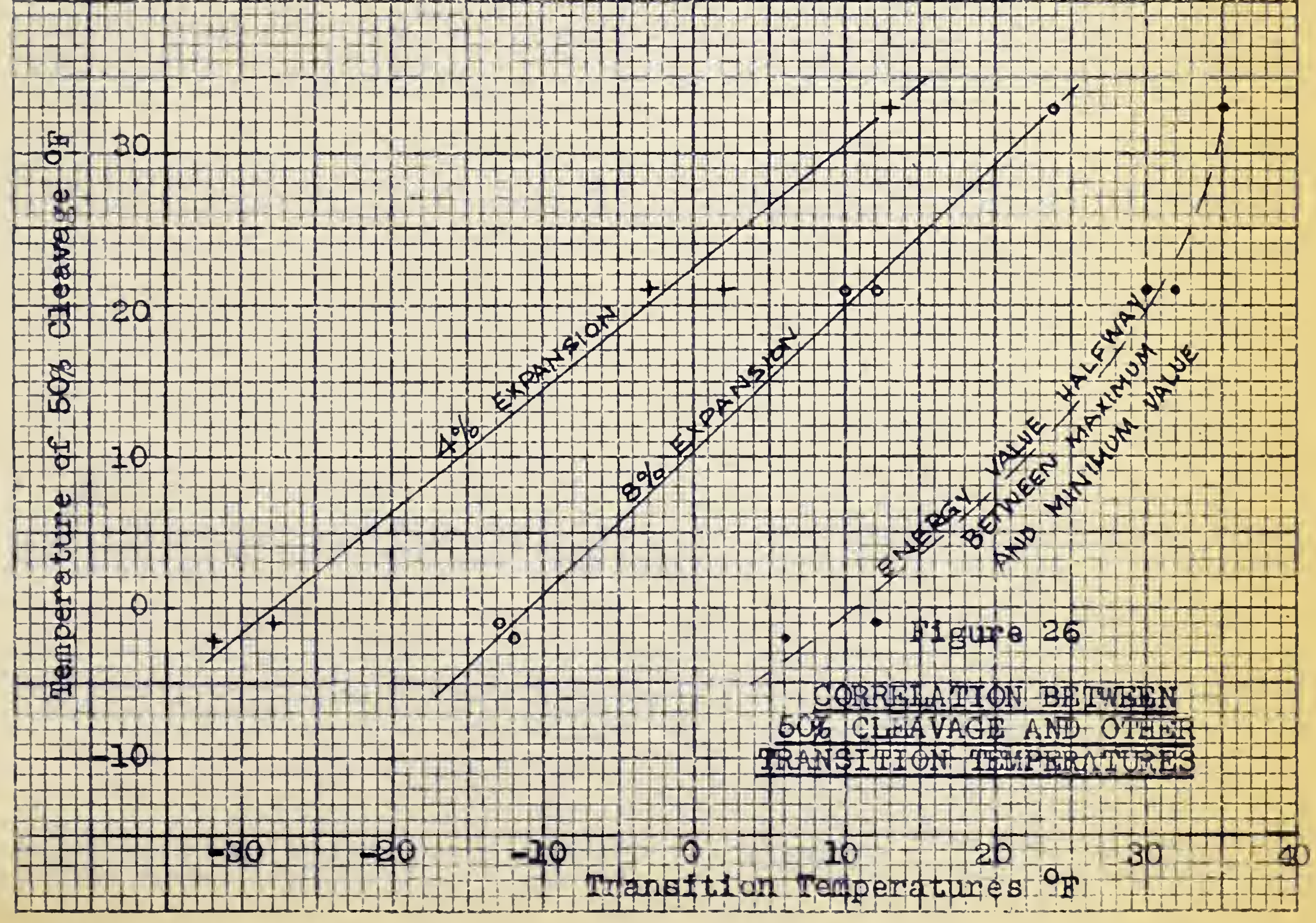


Figure 26

CORRELATION BETWEEN 50% CLEAVAGE AND OTHER TRANSITION TEMPERATURES

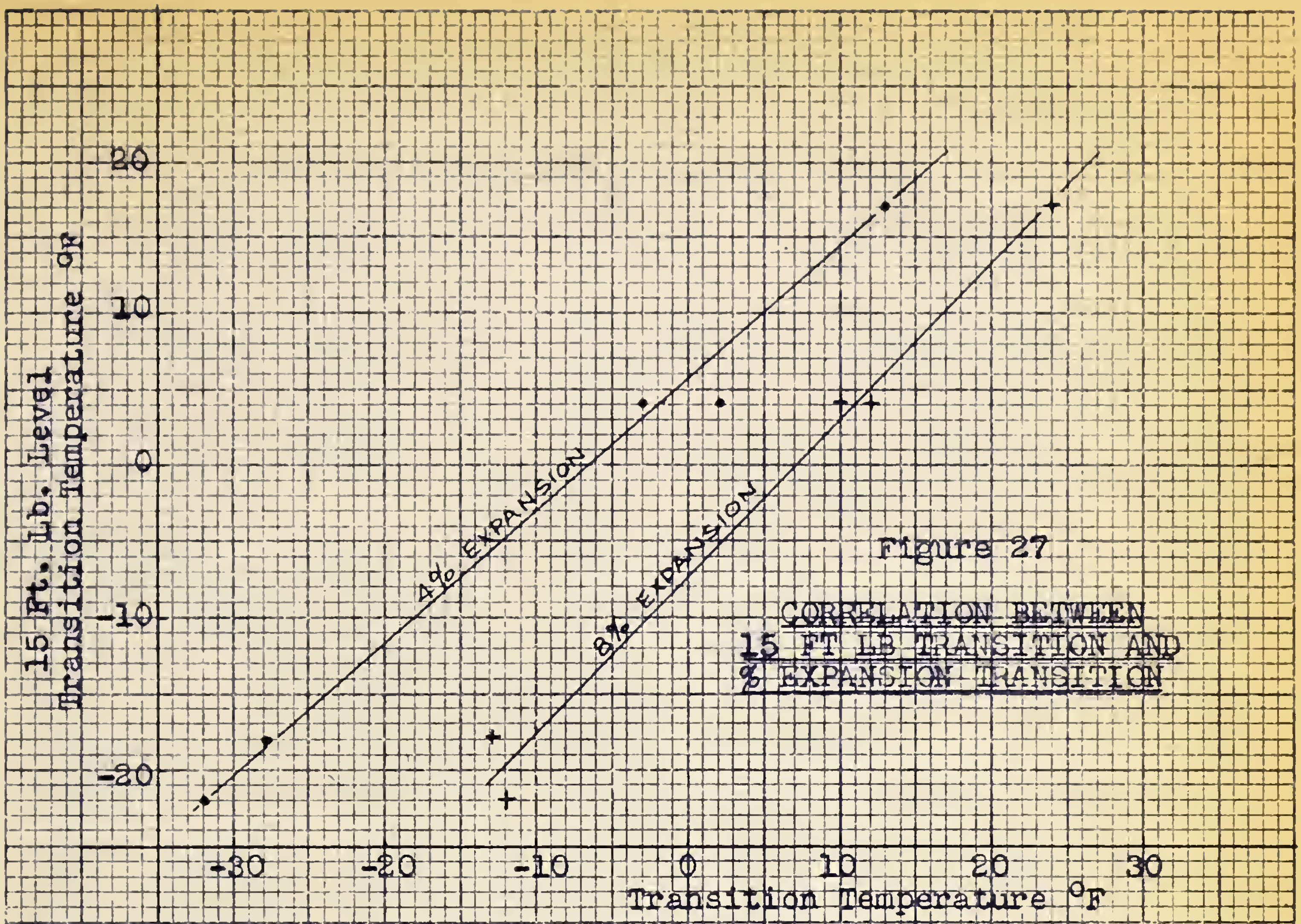


Figure 27

CORRELATION BETWEEN
15 FT LB TRANSITION AND
% EXPANSION TRANSITION

The following relationships exist between the 15 foot pound transition, the 8% Expansion transition and the 50% Cleavage transition as far as the data in this work is concerned.

$$(\text{50\% Cleavage Transition in})\ ^{\circ}\text{F.} = +17.5^{\circ}\ \text{F.} + 0.945 \times (\text{15 ft. lb. Transition}\ ^{\circ}\text{F.})$$

$$(\text{50\% Cleavage Transition in})\ ^{\circ}\text{F.} = +10.0^{\circ}\ \text{F.} + 0.936 \times (\text{8\% Expansion Transition})\ ^{\circ}\text{F.}$$

$$(\text{15 ft. lb. transition})\ ^{\circ}\text{F.} = -7.5^{\circ}\ \text{F.} + 1.042 \times (\text{8\% Expansion transition})\ ^{\circ}\text{F.}$$

8. Summary

Prestraining beyond the yield point increases the transition temperature. The increase is greater for larger amounts of strain. This conclusion is in agreement with the work of others. The transition temperatures were increased an average of 3.5° F. for each 1% prestrain up to 10% prestrain with the average increase above 4° F. for the first 5% and under 3° F. for the second 5% prestrain.

Prestraining below the yield point has a beneficial effect on some definitions of transition temperature. This is particularily true for definitions related to higher absorbed energy levels. For lower energy absorbed levels, there is little change from that of unstrained material.

Prestrain above or below the yield point affects the transition curve by causing a steepening of the transition range. That is, the transition from tough to brittle behavior occurs more quickly once started in strained material than in unstrained material.

The choice of the V-notch Charpy specimen for testing this material was not a good one since the notch was not severe enough to cause all the specimens to break completely. The data nevertheless give comparative results.

Good correlation was found to exist between the 15 foot pound transition, the 50% Cleavage transition, and the 8% Expansion transition. Correlation with other definitions was not too good. The use of the Expansion transition appears to have merit because of the ease of measurement and good correlation with other data although it could only be used on any one type of specimen. Attempts to measure the slope of the transition range were found difficult and did not render useful results.

9. Practical Application:

The effect of prestrain on transition temperature seems to be sufficient to cause the increased incidence of brittle failure of reinforcing hooks during steel handling in cold weather. If the same type of steel as used in these tests was used for reinforcing, there would be an increase of approximately 25° F. in the 15 foot pound V-notch Charpy transition temperature for 5.9% prestrain (the strain at the surface of a standard 180° hook). During investigation of ship plate failures there was a difference of about 20° F. between the 15 foot pound transition temperature of source of fracture plates and the end of fracture or no fracture plates. (6)

There does not appear to be a simple solution to the problem of hook breakages during cold weather. Brittle behavior can be kept to a minimum by using structural grade reinforcing rod rather than intermediate grade during the winter months to keep the carbon content as low as possible, and by using smaller bars to reduce the size effect. There are other possibilities of reducing the tendency for brittle behavior such as normalizing the steel after bending but the cost of such measures would be prohibitive.

Another possible suggestion which could be investigated further involves the effect of temperature at the time of straining on the transition temperature. According to both fabricators and users of reinforcing steel, there is a greater tendency for failure of hooks during handling if the steel is bent while cold compared to room temperature. As far as the writer has been able to determine, the effect of straining temperature on the transition curve has not been fully investigated. A study of this factor could well be the basis of further work on this problem.

H. BIBLIOGRAPHY

1. ASTM Specification A15-58T, Specification for Billet Steel Concrete Reinforcement.

2. Lamb, T., Private communication to Dr. G. Ford, University of Alberta. January 15, 1959.

3. Parr, J. Gordon, Private communication to Canadian Utilities, Limited. October 9, 1957.

4. Parr, J. Gordon, Private communication to Canadian Utilities, Limited. October 2, 1958.

5. Shank, M.E., A Critical Survey of Brittle Failure in Carbon Plate Steel Structures Other Than Ships. ASTM Special Technical Publication No. 158, pp. 45-110, 1953.

6. Parker, E.R., Brittle Behavior of Engineering Structures. New York: John Wiley & Sons, Inc., 1957.

7. Parker, E.R., Theory of Brittle Fracture and Criteria for Behavior at Low Temperatures. ASTM Special Technical Publication No. 158, pp. 116-130, 1953.

8. Rollason, E.C., Metallurgy for Engineers. London: Edward Arnold (Publishers) Ltd., 1956.

9. Scotchbrook, A.F., Eriv, L, Stout, R.D., and Johnston, B.G., Effect of Welding on Pressure Vessel Steels. Transactions ASME, Vol. 72 n 5, July 1958, pp. 539-48.

10. Kenyon, R.L., Burns, R.S., Aging in Iron and Steel. Age Hardening of Metals, pp. 262-313. Cleveland: The American Society for Metals, 1940.

11. Stout, R.D., and McGeady, L.J., Notch Sensitivity of Welded Steel Plate. Welding Journal, Research Supplement, Vol. 28, January 1949, pp. 1s - 9s.

12. Osborn, C.J., Scotchbrook, A.F., Stout, R.D., and Johnston, B.G., Effect of Plastic Strain and Heat Treatment. Welding Journal, Research Supplement, Vol. 28, August 1949, pp. 337s - 353s.

13. Kinzel, A.B., Ductility of Steels for Welded Structures. Metal Progress, Vol. 52, November 1947, pp. 795-799.

14. Tör, Sadun S., Stout, Robert, D. and Johnston, B.G., Further Tests on Effects of Plastic Strain and Heat Treatment. Welding Journal, Research Supplement, Vol. 30 n 11, 1951, pp. 576s - 584s.

15. Tipper, C.F., Private communication to Dr. G. Ford, University of Alberta. October 4, 1958.

16. Tipper, C.F., Effect of Direction of Rolling, Direction of Straining, and Aging on the Mechanical Properties of a Mild-Steel Plate. Journal of the Iron and Steel Institute, October 1952, pp. 143-148.

17. Vanderbeck, R.W., and Gensamer, M., Evaluating Notch Toughness. Welding Journal, Research Supplement, Vol. 28, nl, January 1950, pp. 37s - 48s.

18. Wright, E.C., Notes on the Properties of Carbon Steels Used in Pipe Manufactured for Elevated Temperature Service. Metal Progress, 44 (1943) pp. 1127-1130.

19. Ripling, E.J., Rheotropic Embrittlement. ASTM Bulletin No. 186, December 1952, pp. 37-42 (TP 179-184).

20. Rinebolt, J.A., and Harris Jr., W.J., Statistical Analysis of Tests of Charpy V-Notch and Keyhole Bars. Welding Journal, Research Supplement, Vol. 30. No. 4, April 1951, pp. 202s - 208s.

21. Lorig, C.H., Metallurgical Aspects of Low-Temperature Behavior in Ferrous Materials. ASTM Special Technical Publication No. 158, pp. 147-163 1953.

22. Armstrong, T.N., and Warner, W.L., Low-Temperature Transition of Normalized Carbon-Manganese Steels. ASTM Special Technical Publication No. 176, June 27, 1955, pp. 40-58.

23. Rinebolt, J.A., and Harris Jr., W.J., Effect of Alloying Elements on Notch Toughness of Pearlitic Steels. Transactions ASM, Vol. 45, 1951, pp. 1173-1214.

24. Boulger, F.W., Frazier, R.H., and Lorig, C.H., Investigation of the Influence of Deoxidization and Chemical Composition on Notched-Bar Properties of Ship Plate Steels. Final Report (Project SR-110) National Research Councils Committee on Ship Steel, Ship Structure Committee, 1955.

25. ASTM Specification E8-57T, Tentative Methods of Tension Testing of Metallic Materials.

26. Manual of Standard Practice for Detailing Reinforced Concrete Structures (ACI 315-51). Detroit: American Concrete Institute, 1952.

27. Tipper, C.F., The Brittle Fracture Problem. British Welding Journal, October 1956, pp. 435-439.

28. Williams, M.L., Analysis of Brittle Behavior in Ship Plates. ASTM Special Technical Publication No. 158, pp. 11-44, 1953.

29. ASTM Specification E23-56T, Tentative Methods for Notched Bar Impact Testing of Metallic Materials.

30. Pellini, W.S., Evaluation of The Significance of Charpy Tests. ASTM Special Technical Publication No. 158, pp. 216-257, 1953.

31. Hartblower, Carl E., Transition Behavior in V-Notch Charpy Slow-Bend Tests. ASTM Special Technical Publication No. 176, June 27, 1955, pp. 10-24.

32. Hoyt, S.L., Notched-Bar Impact Tests. Metals Handbook, pp. 112-115. Cleveland: American Society for Metals, 1948.

33. Binder, R.C., Fluid Mechanics. New York: Prentice-Hall, Inc., 1949.

34. Croxton, F.E., and Cowden, D.J., Applied General Statistics. Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1955.

35. Holloman, John H., The Problem of Fracture. New York: American Welding Society, 1946.

36. Timoshenko, S., Theory of Elastic Stability. New York: McGraw-Hill Book Company, Inc., 1936.

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